DUNE: Overview & Science

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P5 Town Hall, Fermilab
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Outline

- DUNE's science goals:
  - Long-baseline neutrino oscillations
  - Supernovae, solar, and other MeV-scale physics
  - Physics beyond the Standard Model
- Questions for this talk:
  - What is the science reach of DUNE Phase I and Phase II?
  - How does DUNE compare to other experiments?
  - What makes DUNE unique?

The 2014 P5 report emphasized the importance of LBNF/DUNE

- Pursue the physics associated with neutrino mass
- Explore the unknown: new particles, interactions, and physical principles

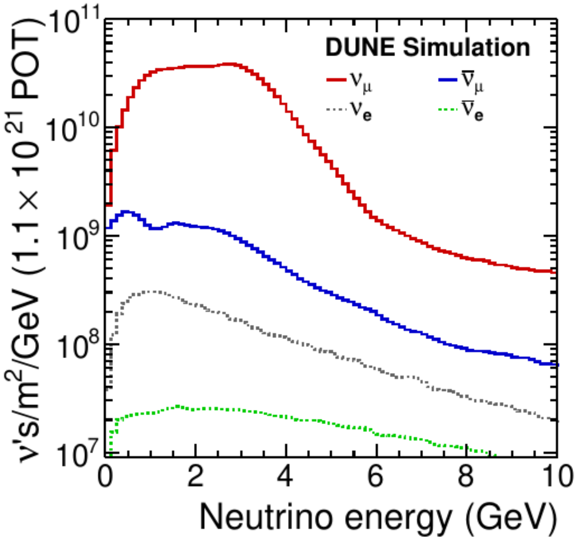
Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

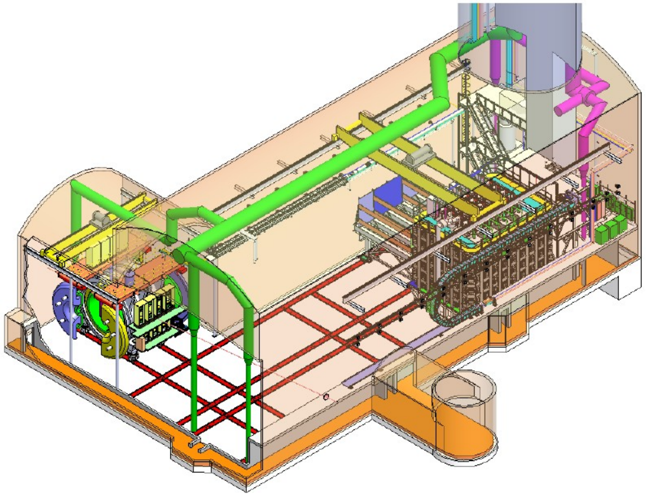
Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

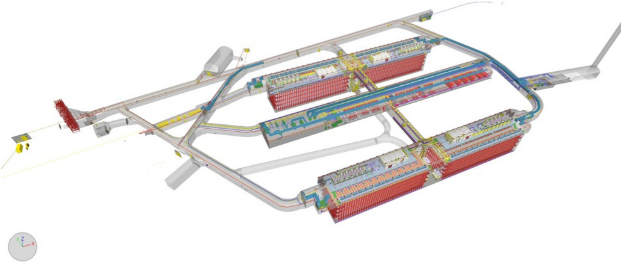
we set as the goal a mean sensitivity to CP violation[2] of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP}.

. With a wideband neutrino beam produced by a proton beam with power of 1.2 MW, this exposure implies a far detector with fiducal mass of more than 40 kilotons (kt) of liquid argon (LAr) and a suitable near detector. **The minimum requirements to proceed are the identified capability to reach an exposure of at least 120 kt*MW*yr by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power.**

DUNE is the result of the 2014 P5 recommendations

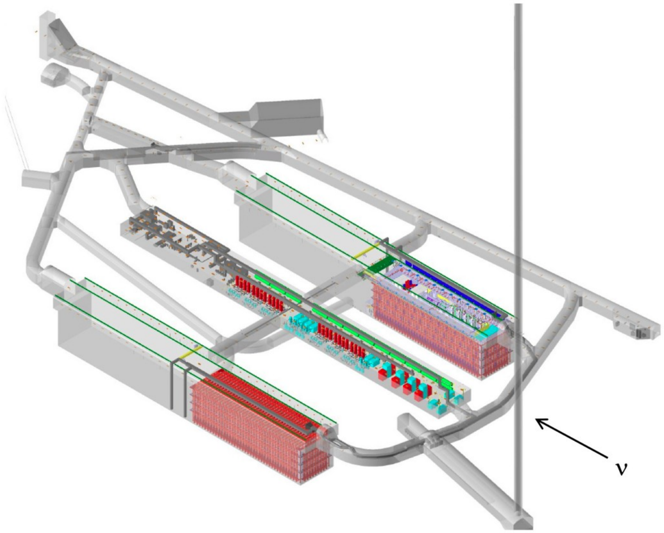


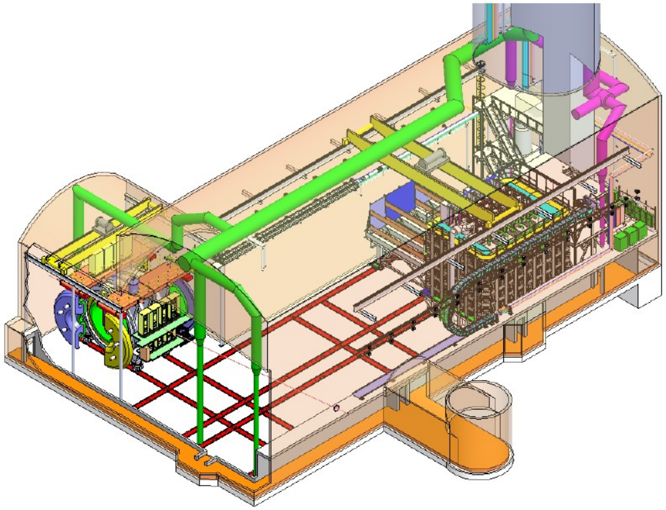




4x17 kt LArTPC, deep underground, wideband beam, suitable ND, and international collaboration

DEEP UNDERGROUND NEUTRINO EXPERIMENT

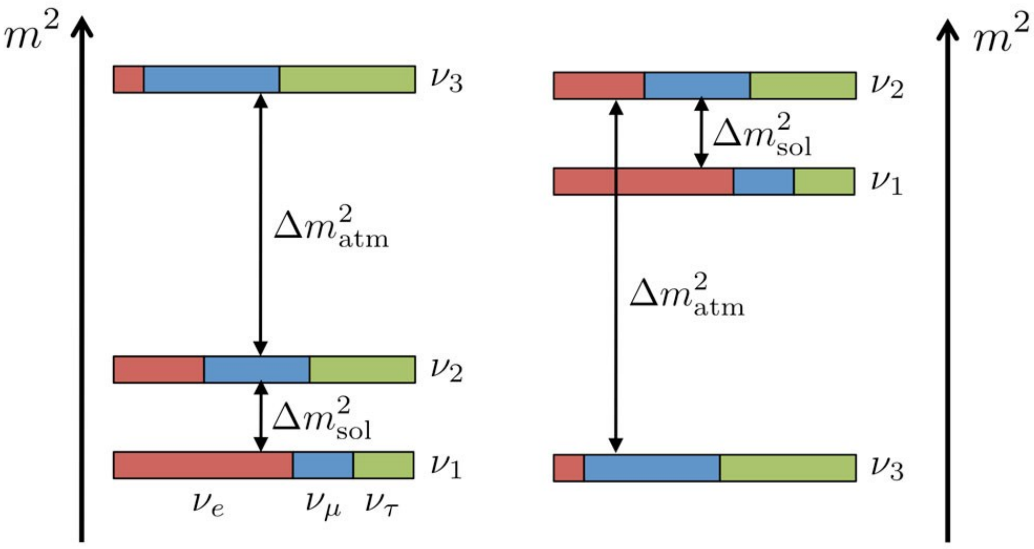




- DUNE Phase I:
  - Full near + far site facility and infrastructure (talk by Chris Mossey)
  - Upgradeable 1.2 MW beam (talk by Rich Stanek)
  - Two 17kt LArTPC modules (talk by Sam Zeller)
  - Movable LArTPC near detector with muon catcher
  - On-axis near detector
- DUNE Phase II:
  - Two additional FD modules (talk by Mary Bishai)
  - Beam upgrade to >2MW (talk by Alexander Valishev)
  - More capable Near Detector (talk by Hiro Tanaka)

Neutrino oscillations: goals

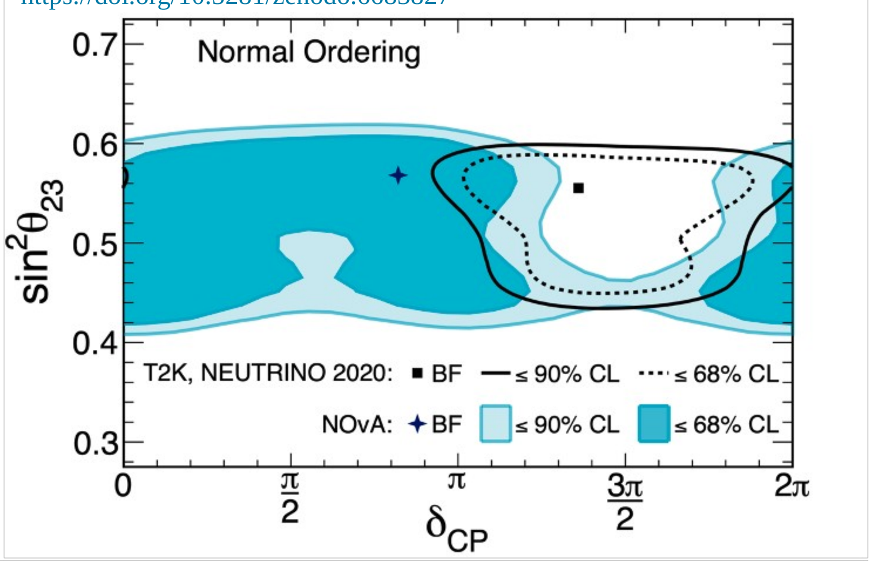
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

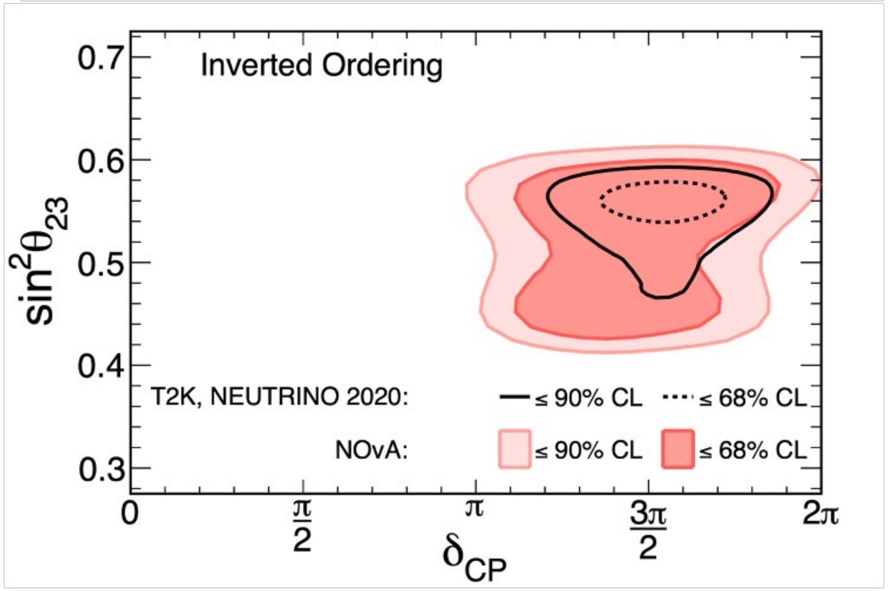


- Measure neutrino mixing:
  - Is there CP violation? How large is it?
  - Are there symmetries? Is $U_{\mu 3} = U_{\tau 3}$?
  - Is the PMNS matrix unitary?
  - What is Δm^2_{32}? Is it positive or negative?
- Search for new physics: Is this three-flavor picture complete?

The picture today: some exclusions but little clarity

https://doi.org/10.5281/zenodo.6683827





- Weak preferences for normal ordering from atmospheric & long-baseline experiments
- Some regions of joint MO-δ_{CP}-θ_{23} space are excluded at >90% by NOvA and T2K
- NOvA and T2K best fit in NO, consistent at ~1σ, but mutually allowed region in IO at <1σ
- **We really do not know the mass ordering or δ_{CP}**
- **We need definitive experiments**

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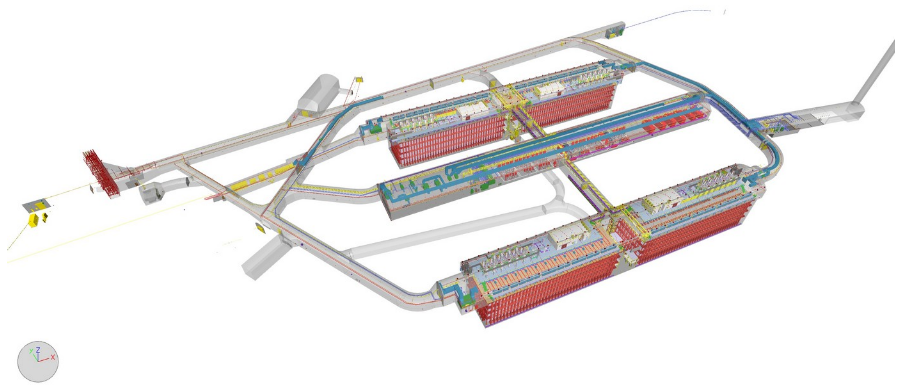
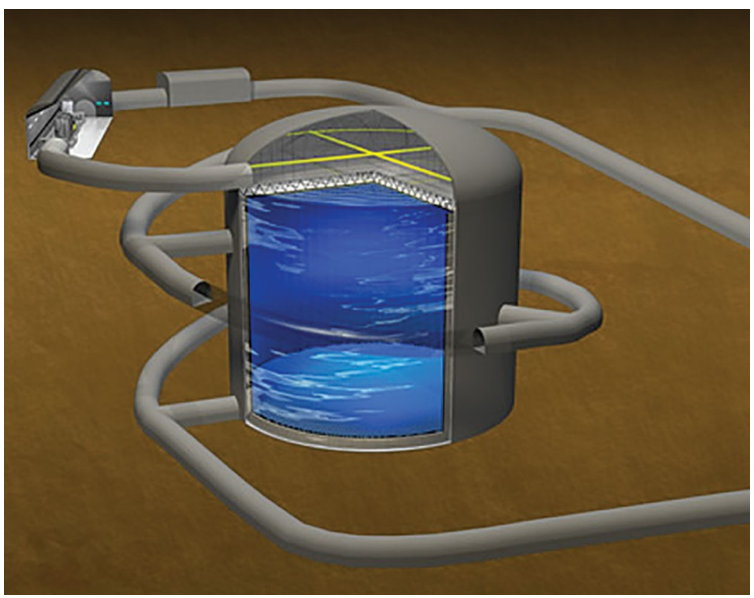
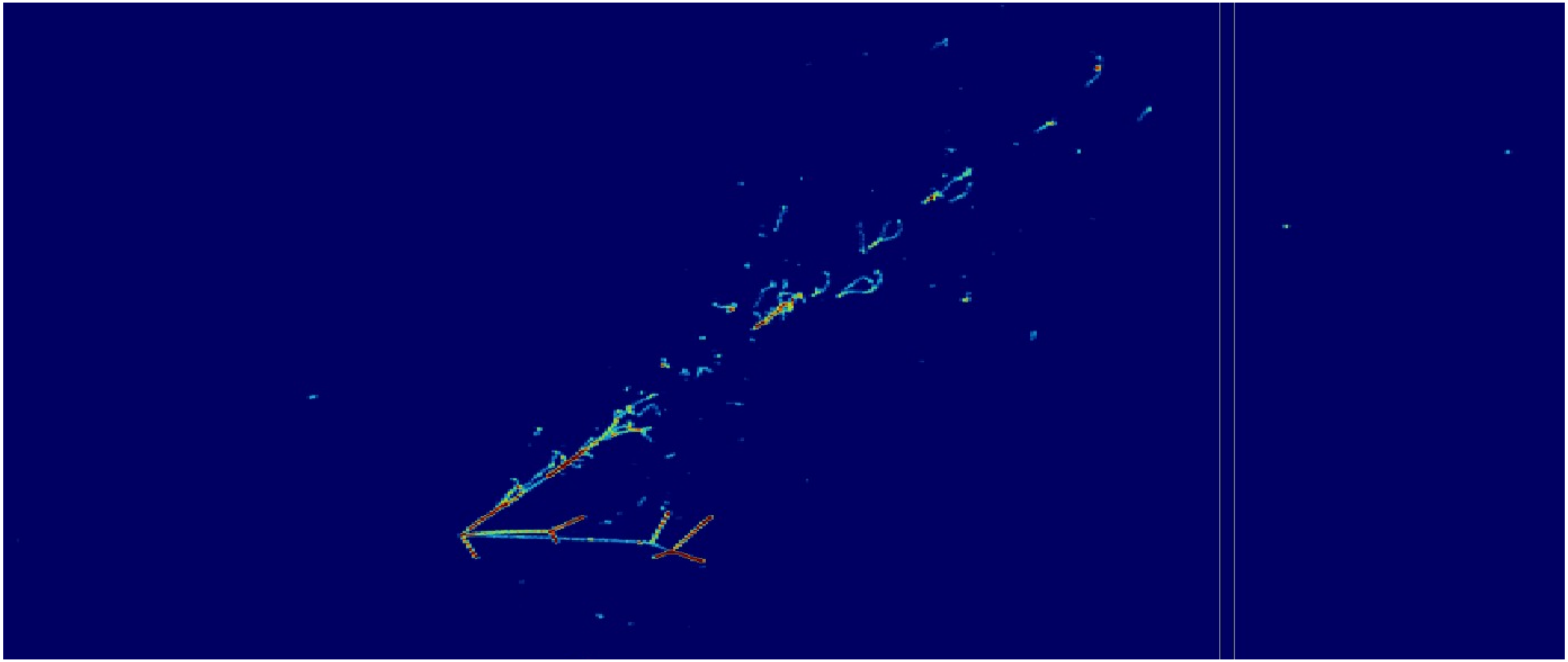
DUNE and Hyper-K: different strategies, different detectors





- DUNE:
  - Very long baseline → large matter effect → unambiguous mass ordering and CPV
  - Broadband neutrino beam → high statistics over full oscillation period
  - Reconstruct E_ν over broad range → imaging + calorimetry → LArTPC technology
  - Highly-capable near detector to constrain systematic uncertainties
- Hyper-K:
  - Shorter baseline → small matter effect
  - Off-axis location & narrowband beam → very, very high statistics at oscillation maximum, less feed-down
  - Lower energy and mostly CCQE → very large water Cherenkov detector
  - Highly-capable near detector to constrain systematic uncertainties

How DUNE sees neutrinos and measures oscillations



- Identify as ν_e CC from electromagnetic shower
- Measure E_ν by summing the energy of the electron and hadrons (one pion and two protons, in this case)

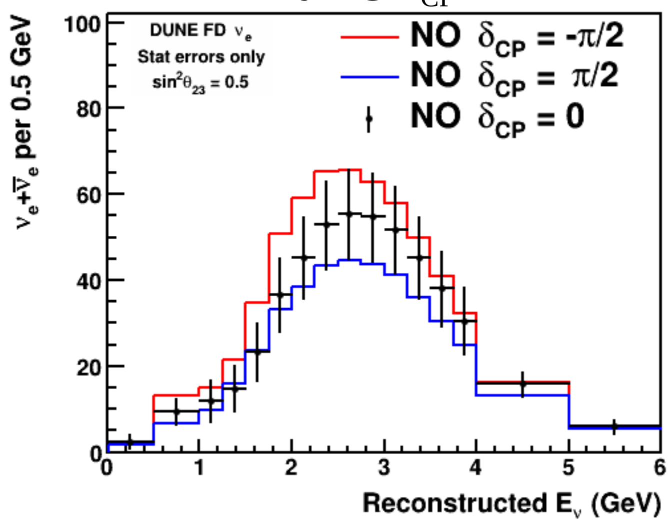
DUNE ν_e and $\bar{\nu}_e$ spectra can distinguish MO in Phase I

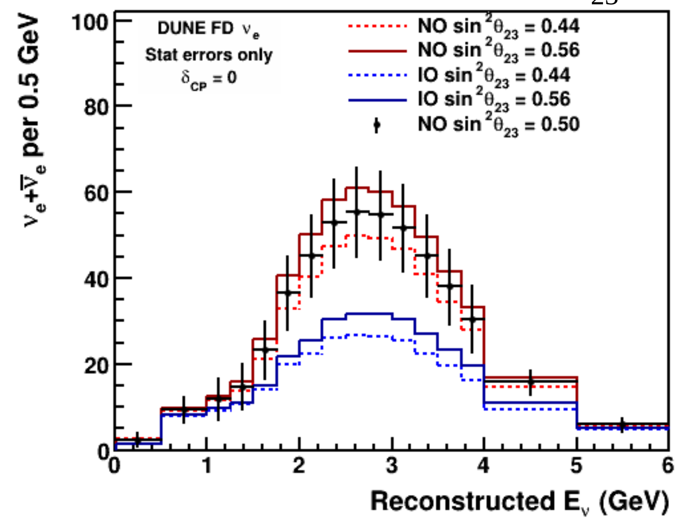
Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

Varying δ_{CP}

Varying MO and $\sin^2\theta_{23}$

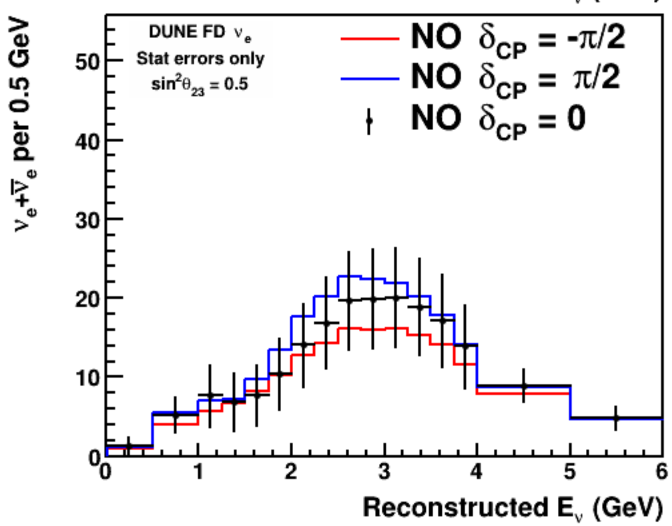
Neutrino mode

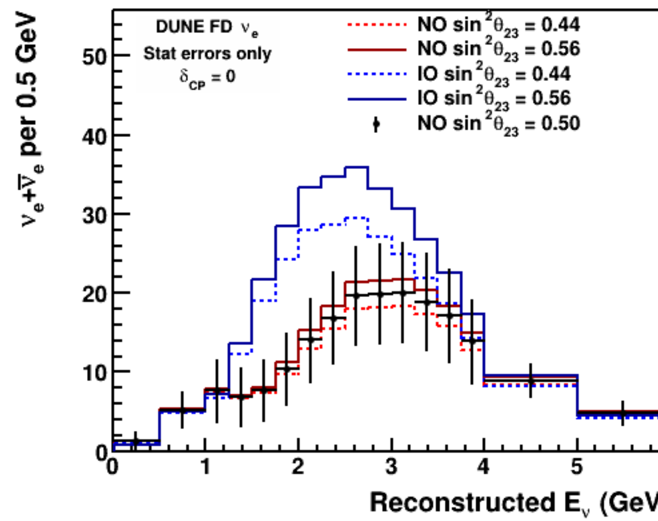




Phase I

Antineutrino mode





DUNE ν_e and $\bar{\nu}_e$ spectra can measure δ_{CP}, θ_{23} octant in Phase II

Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

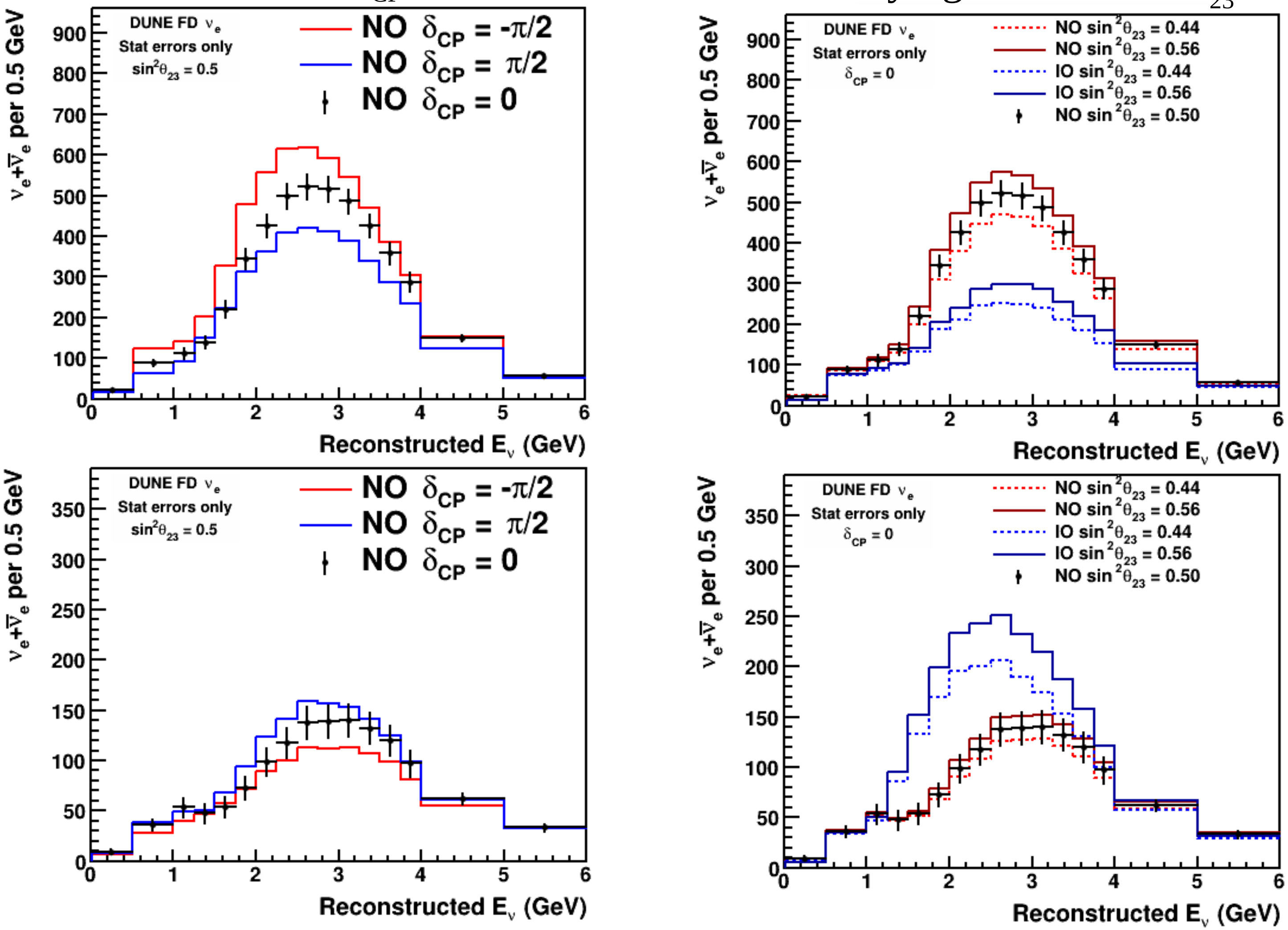
Varying δ_{CP}

Varying MO and $\sin^2\theta_{23}$

Neutrino mode

Phase II

Antineutrino mode



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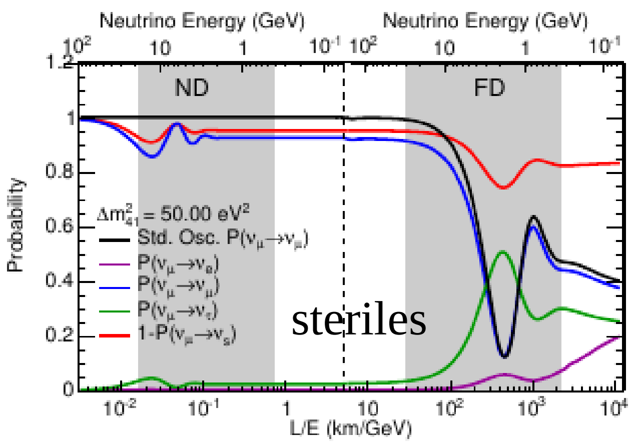
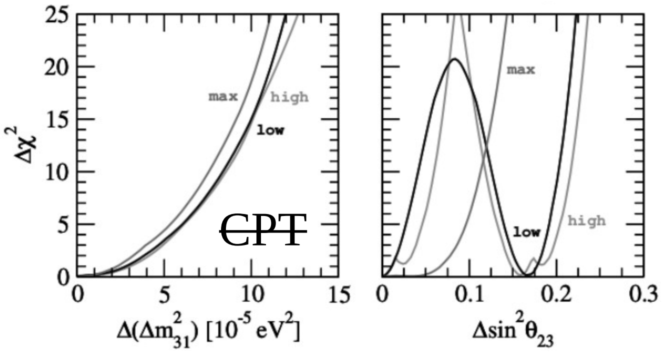
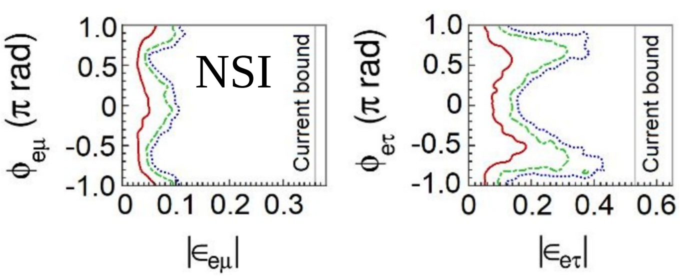
DUNE is sensitive to new physics in neutrino oscillations

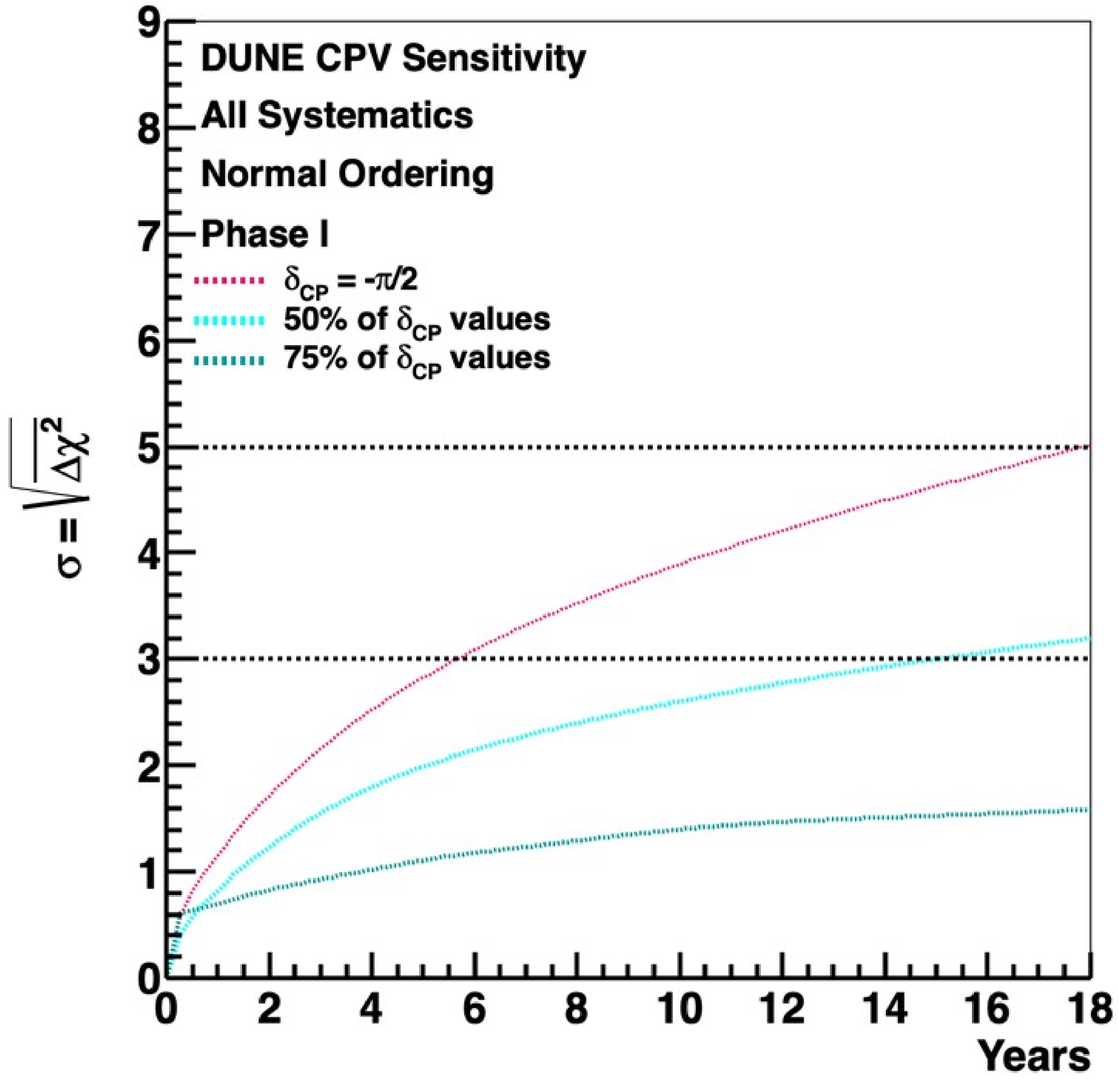






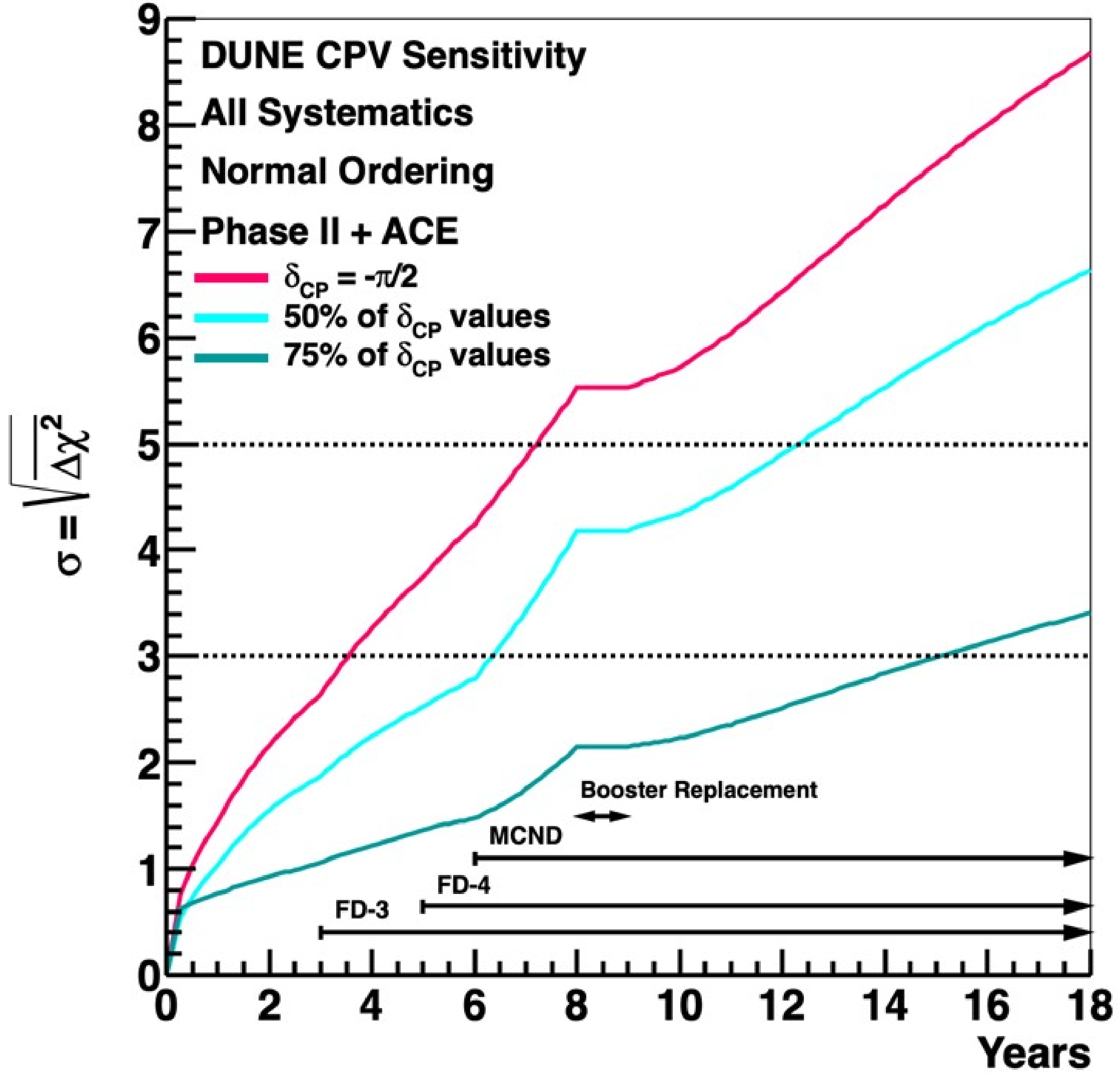
- If ν and $\bar{\nu}$ spectra are inconsistent with three-flavor oscillations, it could be due to sterile neutrinos (top), CPT violation (middle), or NSI (bottom)
  - DUNE covers a very broad range of L/E at both the ND and FD
  - DUNE can measure parameters like Δm^2_{32} with neutrinos and with antineutrinos
  - DUNE has unique sensitivity to NSI matter effects due to long baseline
- Characterizing new physics will be challenging: precise measurements with small matter effect in Hyper-K **and** large matter effect in DUNE Phase II likely required

Phase II is required to establish CP violation at high significance



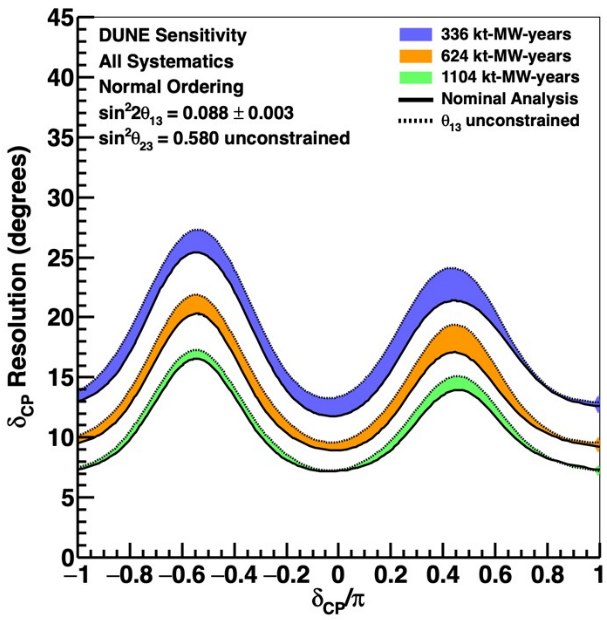
- If $\delta_{CP} = \pm 90°$, DUNE can establish CP violation at 3σ in Phase I
- For all other oscillation scenarios, DUNE requires Phase II to establish CP violation

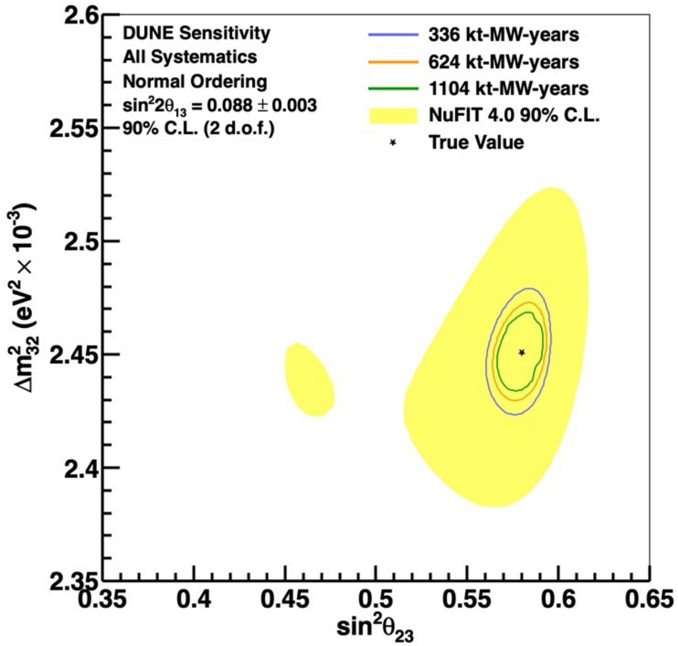
Timeline for CP violation: it depends on the value of δ

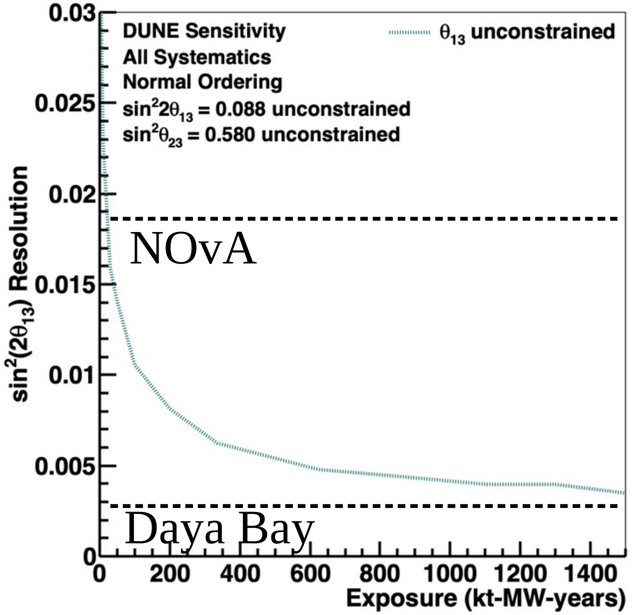


- If $\delta_{CP} = \pm 90°$, DUNE reaches 3σ CPV in 3.5 years, 5σ in 7 years
  - Hyper-K will likely get there first, if/when the mass ordering is known
- If $\delta_{CP} = \pm 23°$, it is extremely challenging to establish CP violation at 3σ → DUNE and Hyper-K are competitive and complementary

DUNE Phase II: precision long-baseline physics



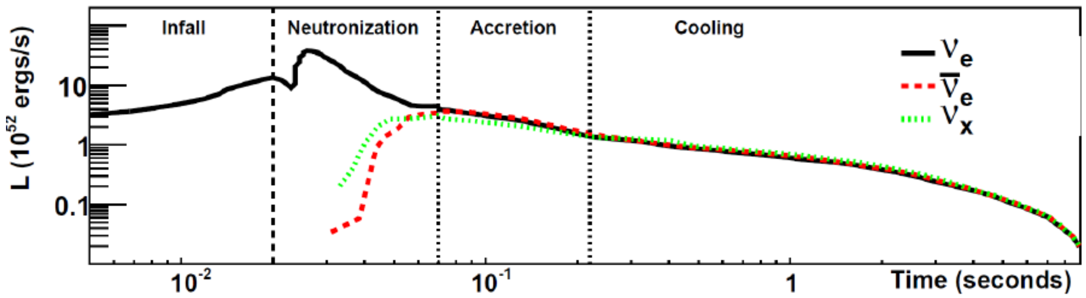


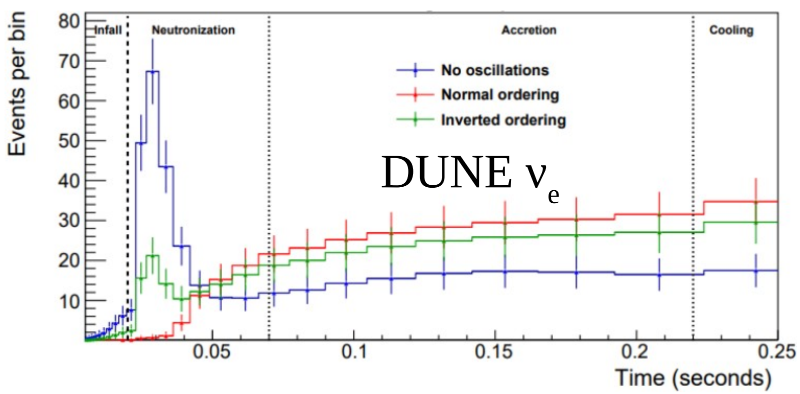


- Resolution to δ_{CP} is ~6-16° depending on true value, and sensitivity to CPV even if Nature is relatively unkind
- Excellent resolution to θ_{23}, including octant discovery potential
- Resolution to θ_{13} approaches Daya Bay, DUNE-reactor comparison is sensitive to new physics

Supernova physics: unique sensitivity to electron neutrinos

10 kpc supernova burst



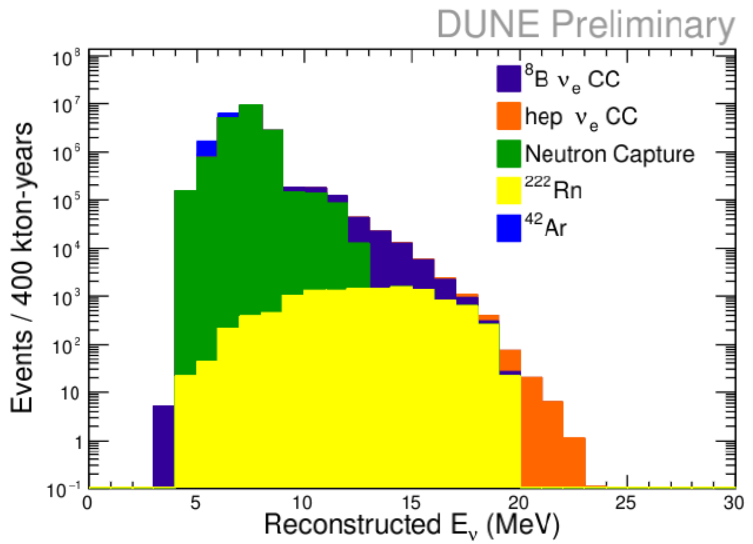


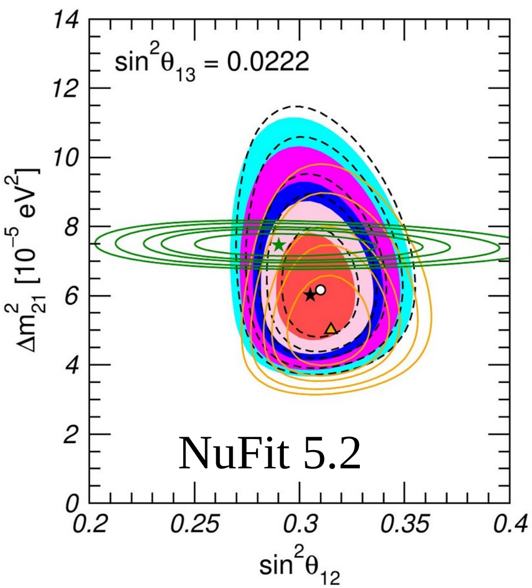
	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

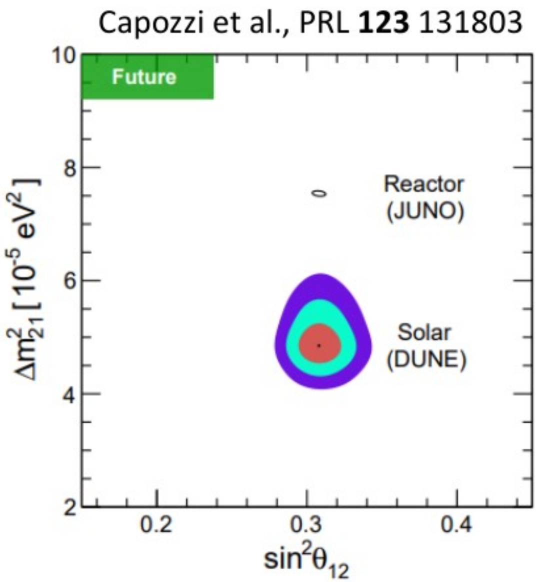
[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

- Time (and energy) profile of the flux is rich in supernova astrophysics
- Flux contains ν_e and $\bar{\nu}_e$ as well as a component of the other flavors (ν_x) – DUNE has **unique sensitivity to ν_e** component
- Phase I: O(100s) events per FD module for galactic SNB
- Phase II: Reach extends reach beyond the Milky Way
- Enhancements to LArTPC design in Phase II could greatly extend low energy science (see talk by Mary Bishai)

Solar neutrinos: search for new physics with DUNE and JUNO

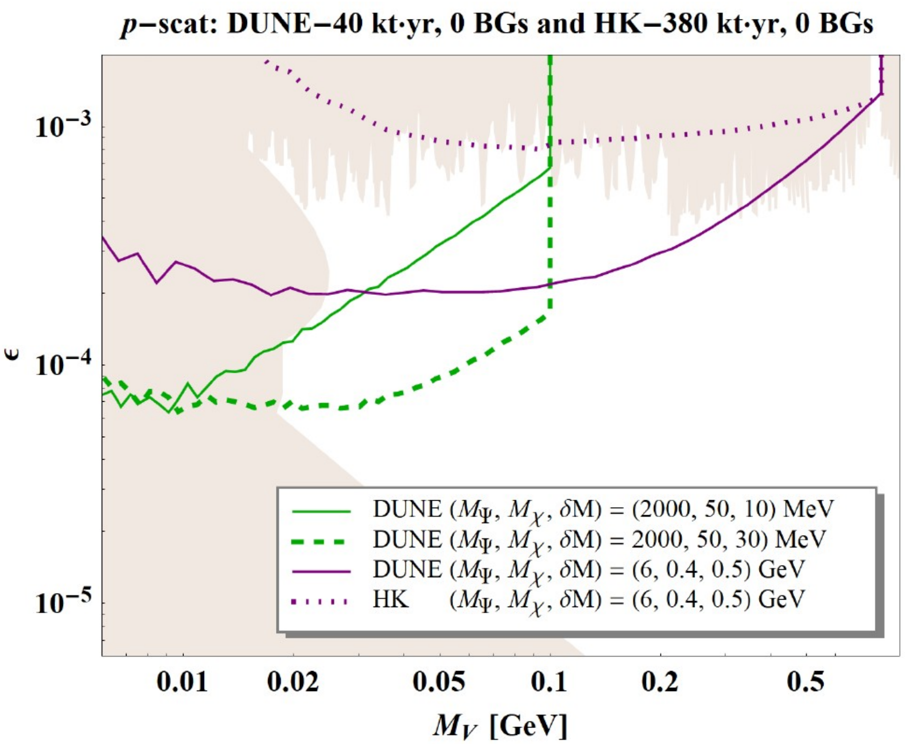


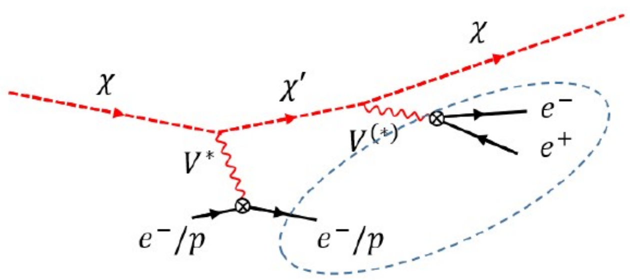




- Despite large neutron background below ~10 MeV, DUNE can measure ^8B solar flux and observe hep flux
- Phase I: >5σ sensitivity to hep flux
- Phase II: DUNE can improve existing θ_{12} and Δm^2_{21} measurements with solar neutrinos
- JUNO will have by far the best precision in θ_{12} and Δm^2_{21}; DUNE-JUNO comparison is sensitive to new physics

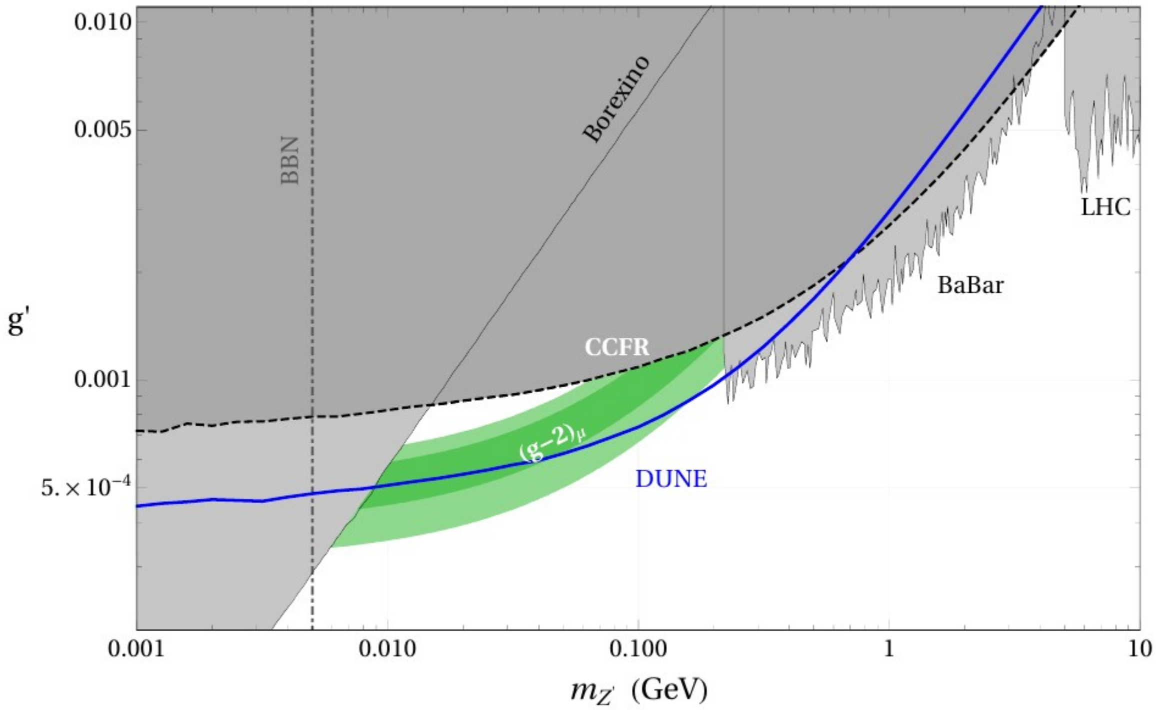
BSM physics: unique capabilities of the DUNE Far Detector

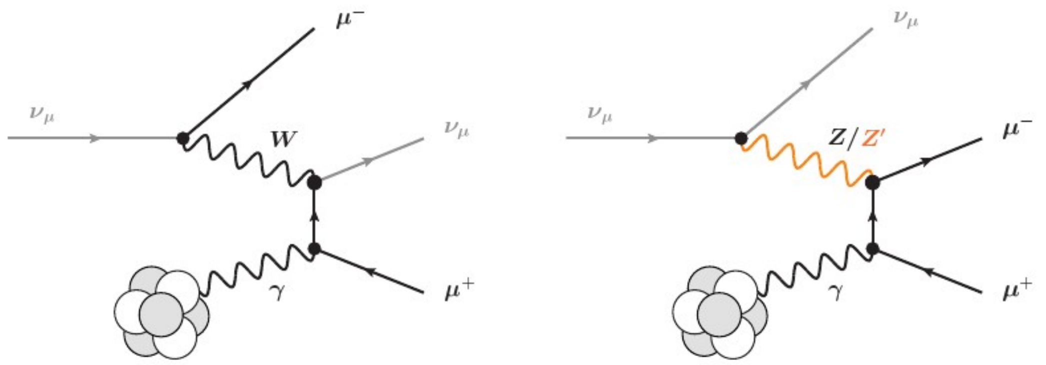




- Hyper-K will have higher statistics, but DUNE's imaging and spatial resolution are critical for some signals
- Inelastic dark matter scattering gives a signature of two low-energy electron tracks, and a detached low-energy electron or proton
- DUNE can see all of these tracks, and the displacement → world leading sensitivity at low mass already in Phase I
- Strong connection to theory community → what new physics can we search for, and what would the signal be?

BSM physics with the LBNF beam: Neutrino tridents at the ND



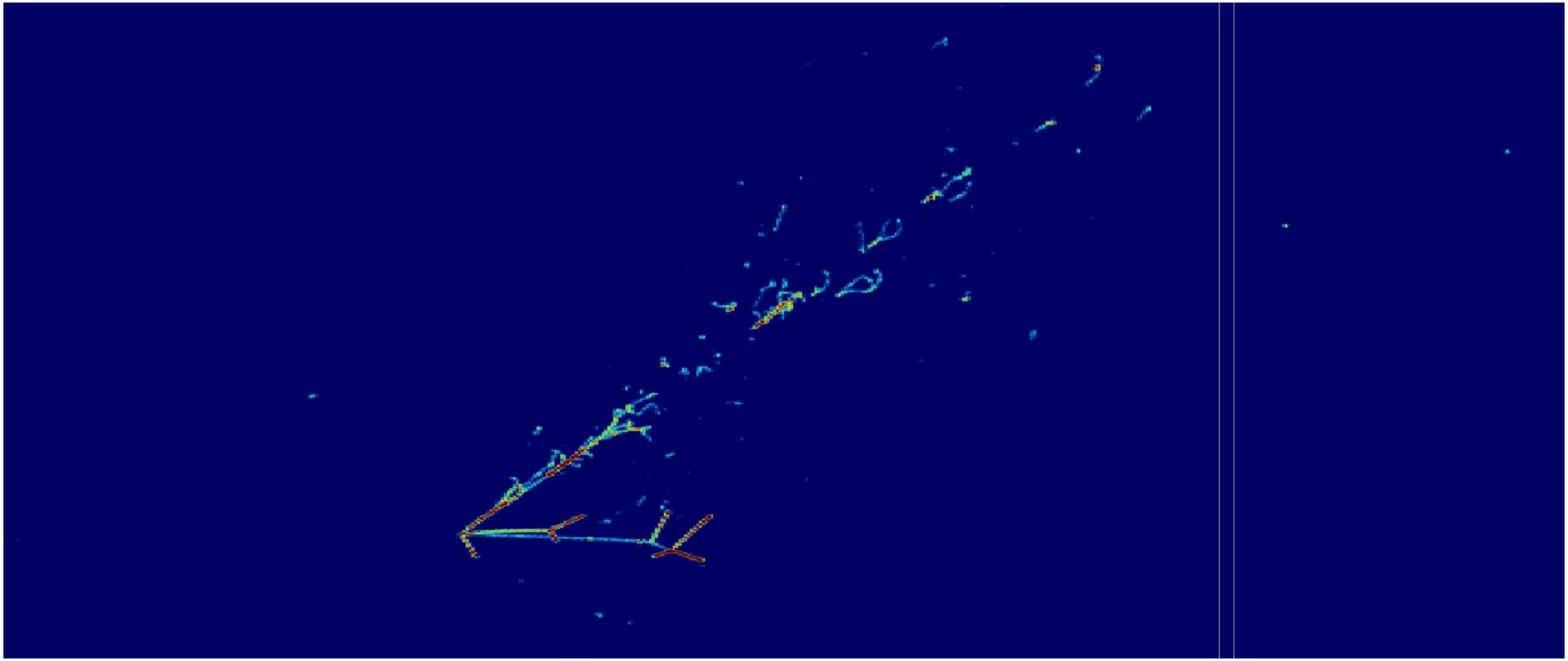


- DUNE ND-LAr will see ~100 μμ tridents per year (at 1.2 MW; XS scales with energy and Z^2)
- Backgrounds (mainly CC1π) can be mitigated by requiring clean vertex, two long, non-scattering tracks
- Tiny SM cross section, DUNE can search for enhancement due to Z'
- World-leading reach at low Z' mass is complementary to collider searches, and covers much of the remaining region that is consistent with a possible $(g-2)_\mu$ anomaly
- Also at ND (in backups): Heavy neutral leptons, boosted dark matter

Conclusions

- DUNE is a best-in-class long-baseline neutrino oscillation experiment
  - Mass ordering and initial measurements in Phase I
  - CP violation, precision measurements, and search for new physics in Phase II
- DUNE has unique sensitivity to MeV-scale neutrinos
  - Only experiment sensitive to Supernova ν_e
  - Detection of hep solar flux and measurement of solar parameters
  - Opportunities to greatly enhance LE reach in Phase II
- DUNE has a rich and broad BSM program
  - BSM oscillations with large L/E range and large matter effect
  - Direct detection sensitivity, especially to low-energy hadrons
- DUNE is both competitive with, and complementary to the global experimental program

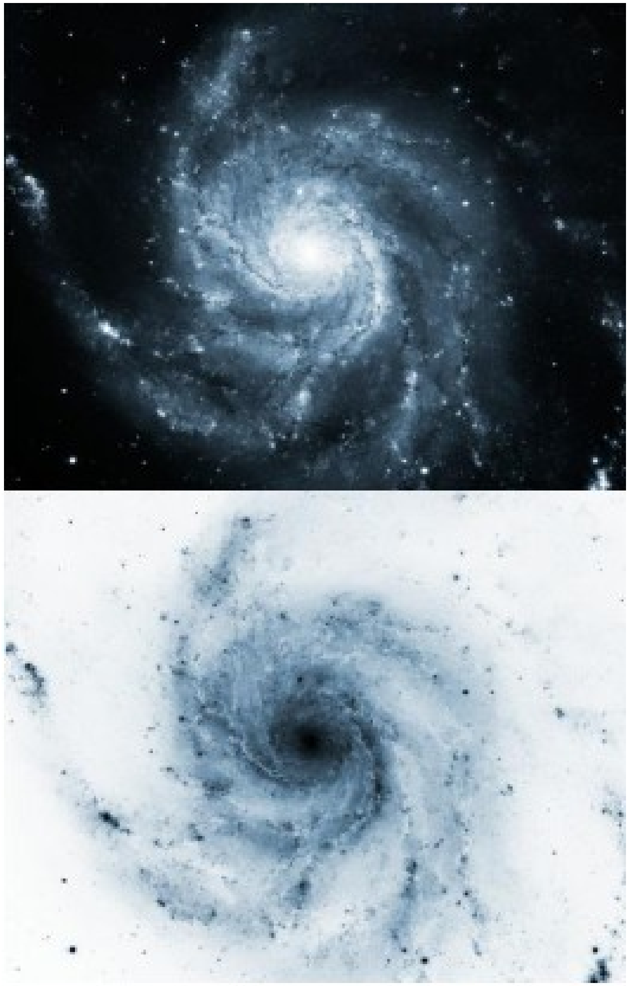
Thank you



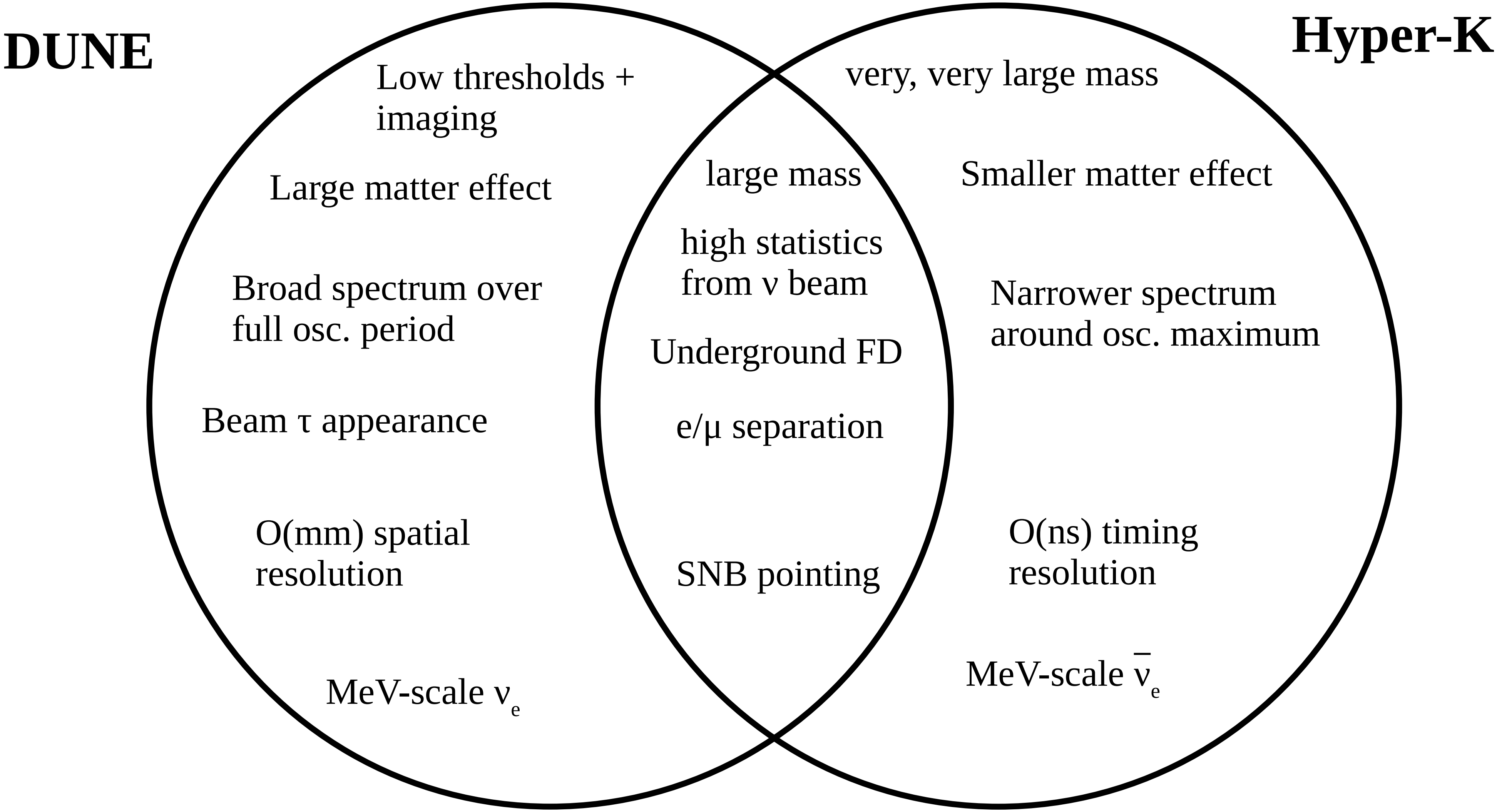
Backup

Neutrino oscillations: Big picture questions

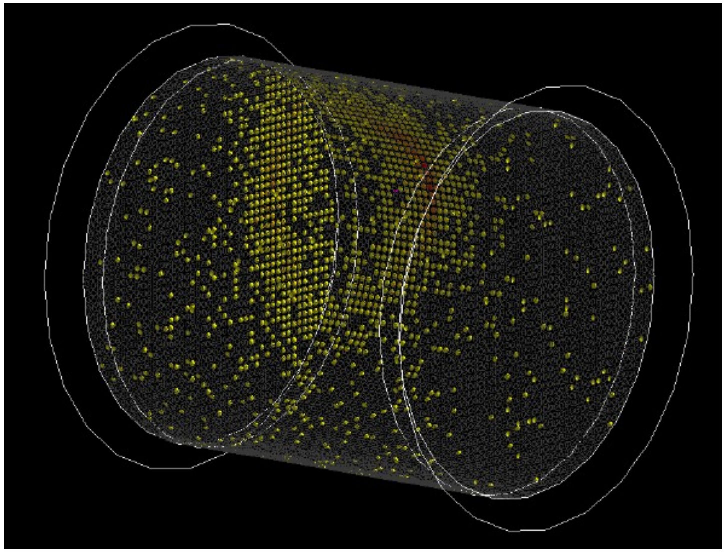
- What is the origin of neutrino mixing? Is there an underlying flavor symmetry, and how is it broken?
- What is the origin of the neutrino masses? Why are the neutrinos so light?
- Is leptogenesis a viable explanation of the baryon asymmetry of the Universe?
- Is the νSM complete? Are there additional neutrinos?

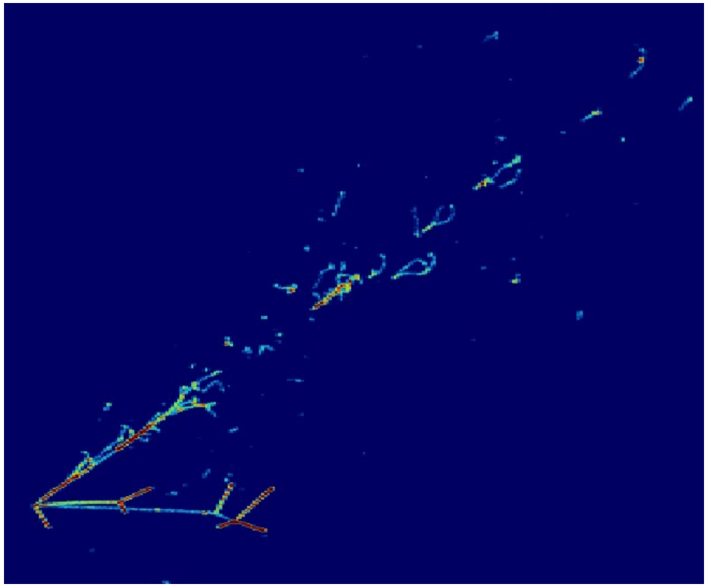


Complementarity



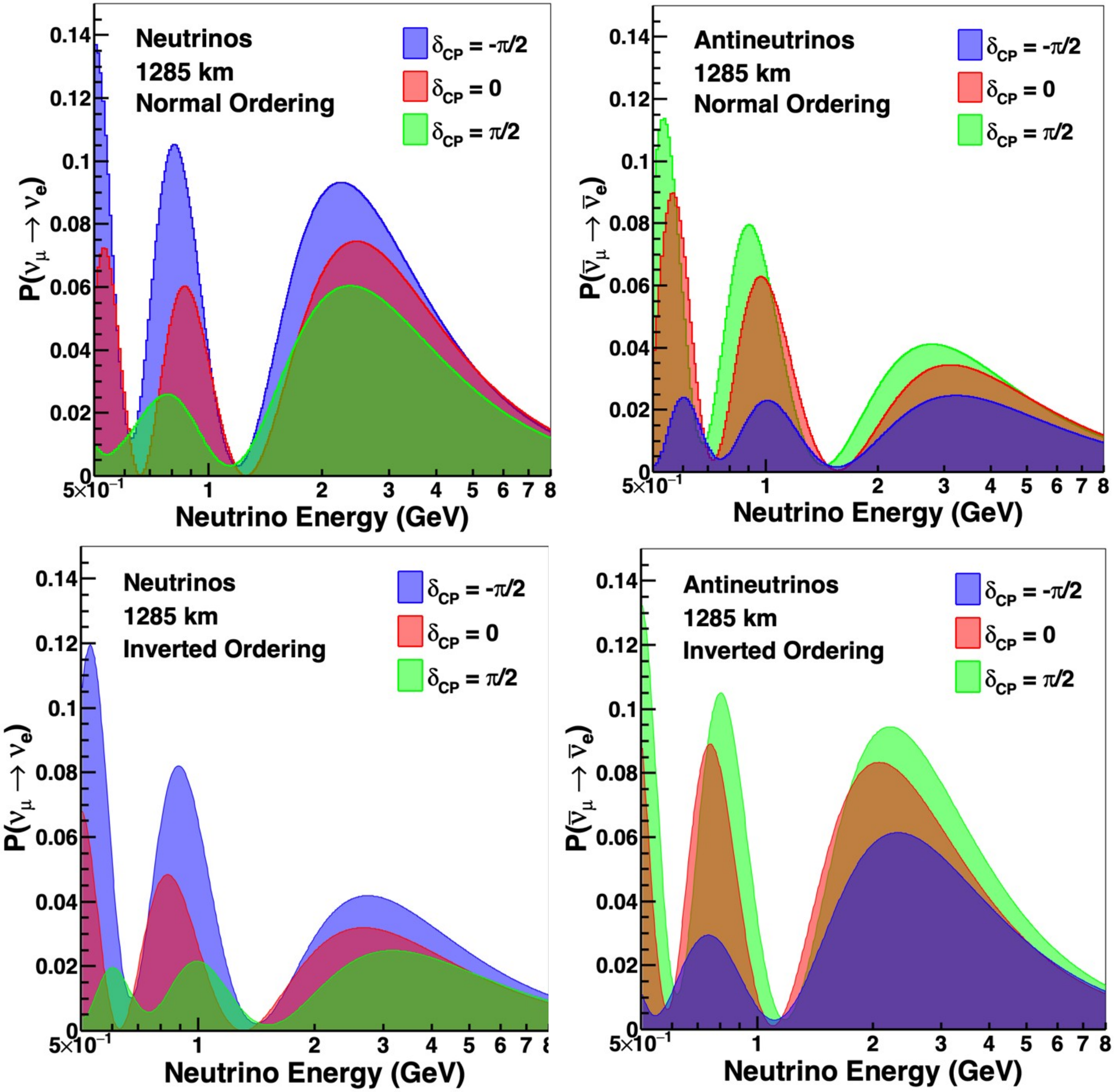
Different optimizations → different strengths for non-beam physics





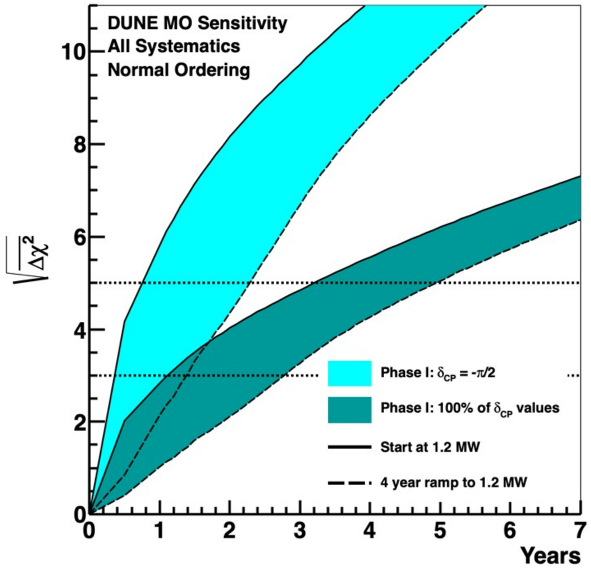
- Pictured: ν_e CC interaction in Hyper-K and DUNE
- For long-baseline oscillation physics, Hyper-K and DUNE are both well suited for their respective neutrino beams
- For non-beam physics, Hyper-K and DUNE are very complementary:
  - Hyper-K has higher mass, better timing
  - DUNE has lower thresholds for charged particles, better imaging and event identification

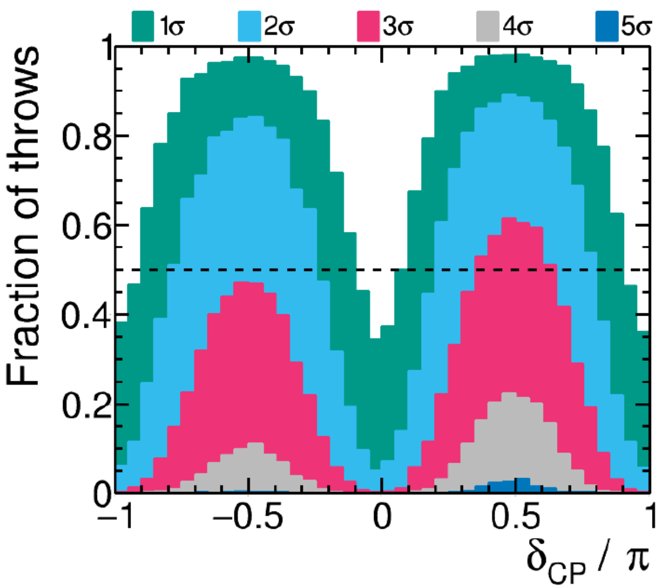
DUNE: large matter effect, broad neutrino beam



- Large matter effect → CPV and mass ordering are totally non-degenerate
- Spectral information resolves degeneracies between θ_{23}, θ_{13}, and δ_{CP}, and enables searches for non-standard oscillations

DUNE Phase I: definitive mass ordering, possible hints of CPV

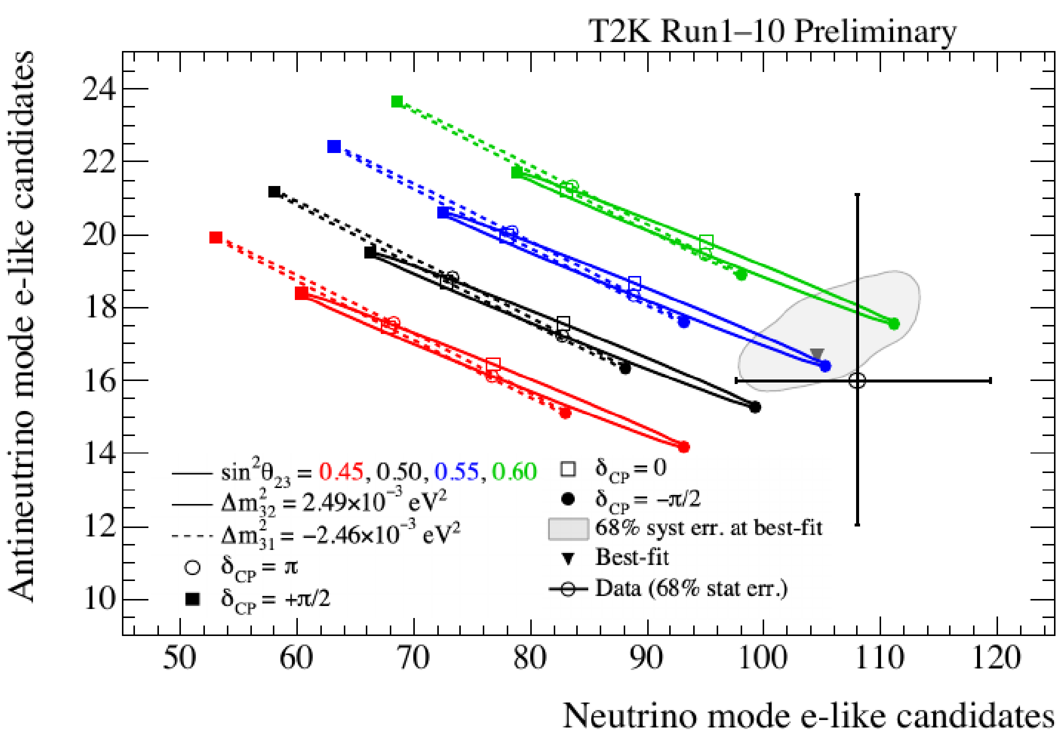


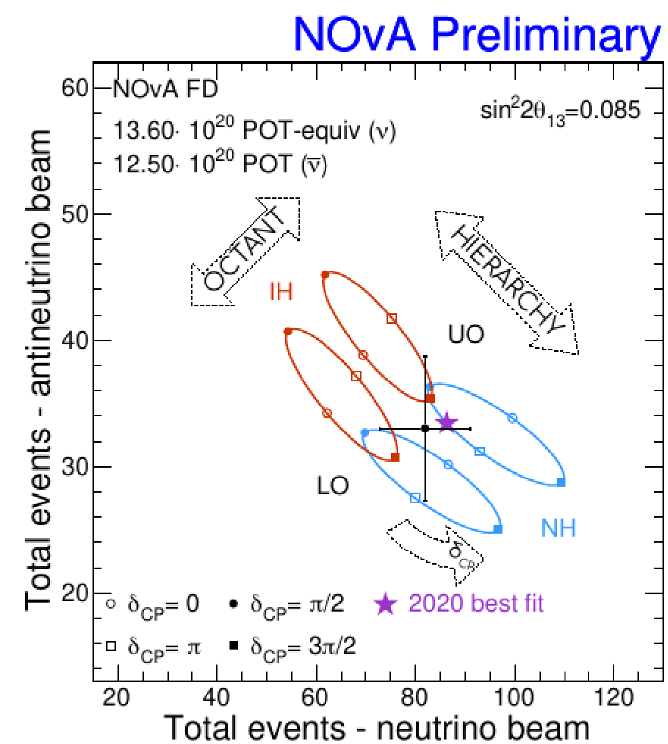


- Large matter effect in DUNE → mass ordering is "easy"
- DUNE will have >5σ significance after 1-4 years of Phase I, depending on true δ_{CP}
- DUNE has ~3σ sensitivity to CP violation in Phase I, but only if CPV is nearly maximal
  - ~50% chance of 3σ if $\delta_{CP} = \pi/2$
  - ~20% chance of 3σ if $\delta_{CP} = \pi/4$

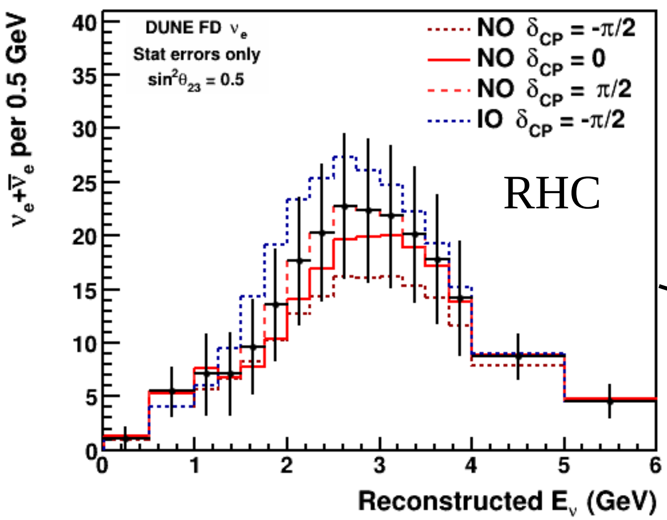
NOvA and T2K bi-event plots

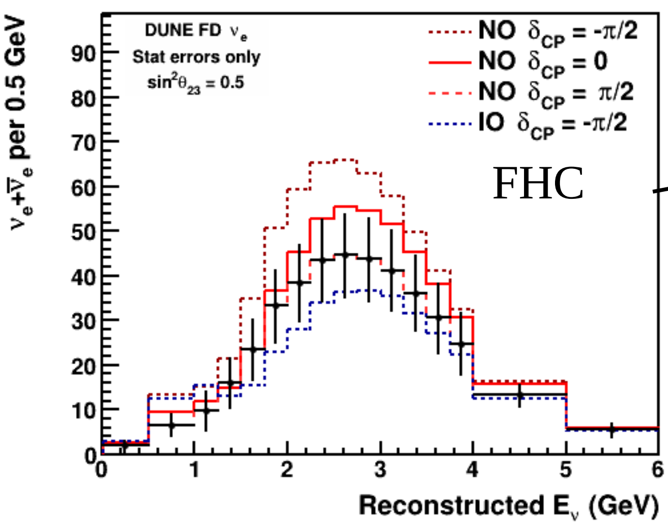
- Count ν_e events in neutrino mode (x axis), and count $\bar{\nu}_e$ in antineutrino mode (y axis)
- Ellipses represent the cyclical effect of δ_{CP}
- Matter effect splits the NH and IH ellipses about y=x
- $\sin^2\theta_{23}$ moves ellipses along y=x

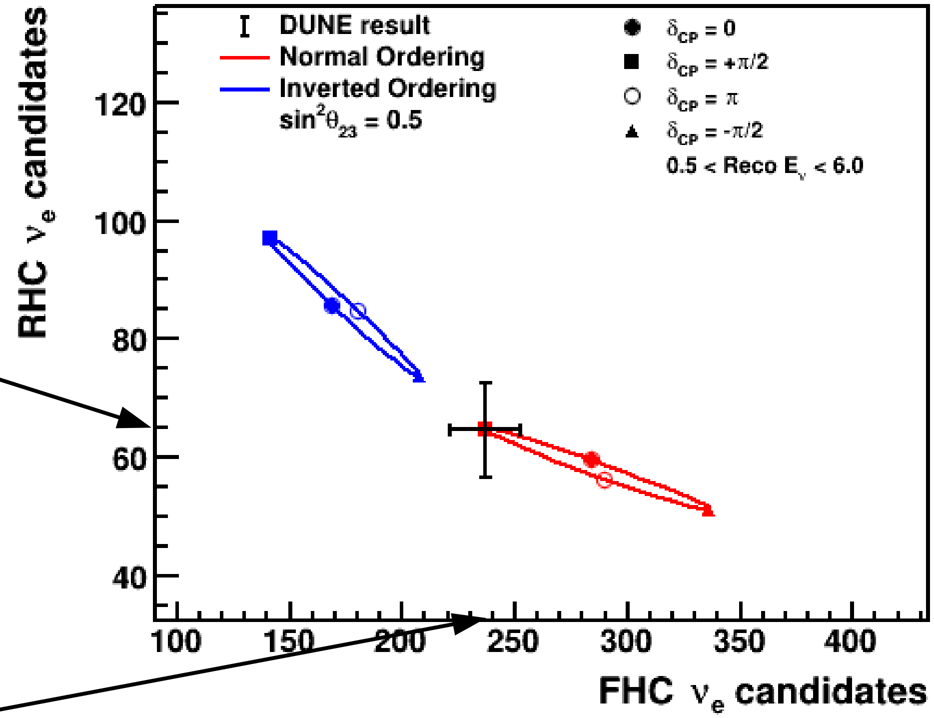




A “bi-event” plot is not a great way to represent DUNE data

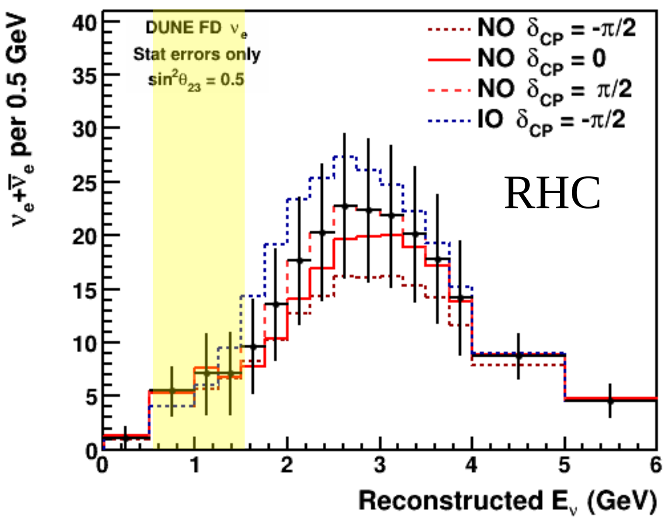


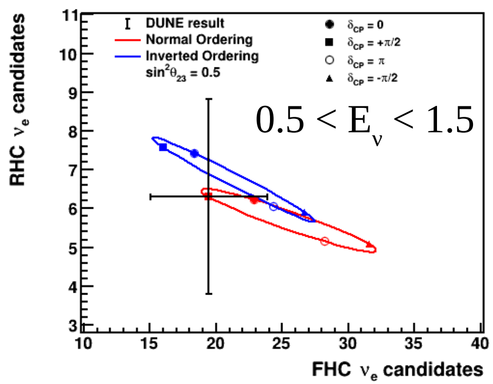


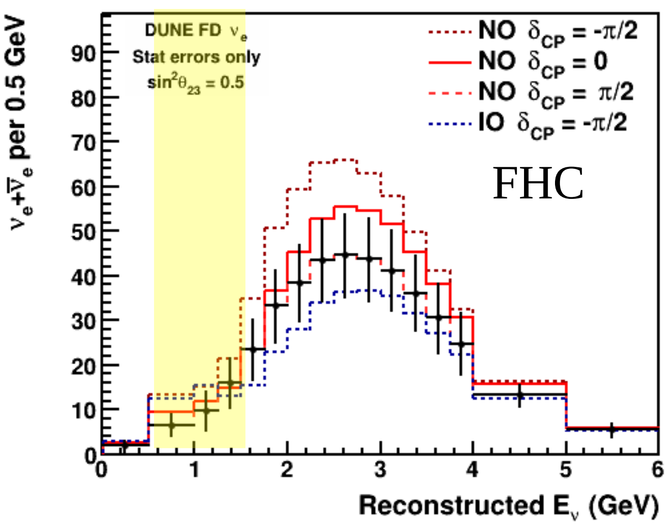


- Discarding all spectral information, DUNE can also make a bi-event plot
- The normal and inverted ordering ellipses do not touch → there is no degeneracy between mass ordering and CP violation measurements by 4 years

DUNE can do this in many energy bins over full oscillation period

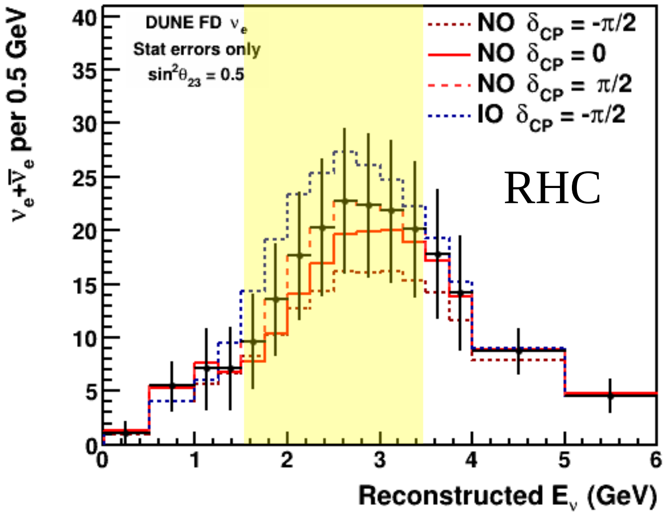


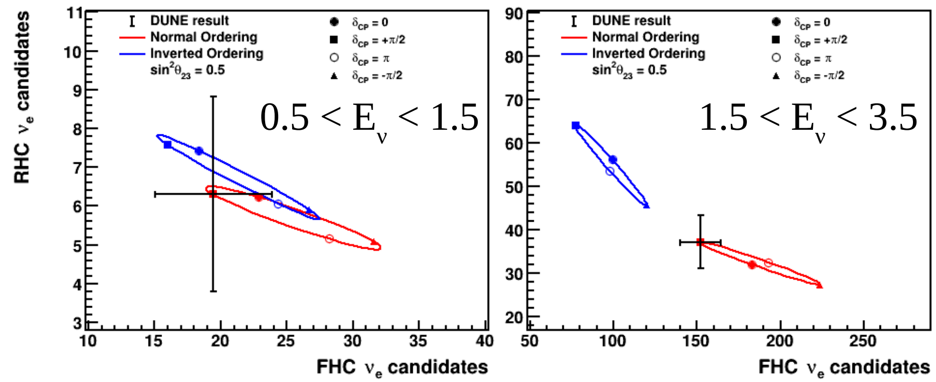


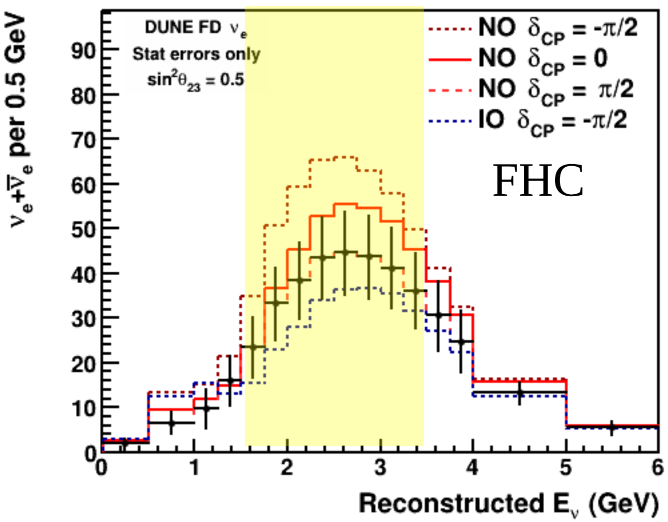


- As an illustration, we can divide the sample into just three energy bins
- This is still a huge understatement of DUNE's capability – our actual oscillation analysis uses 17 energy bins
- There is no separation between the mass orderings at low energy because the matter effect scales with energy

DUNE can do this in many energy bins over full oscillation period

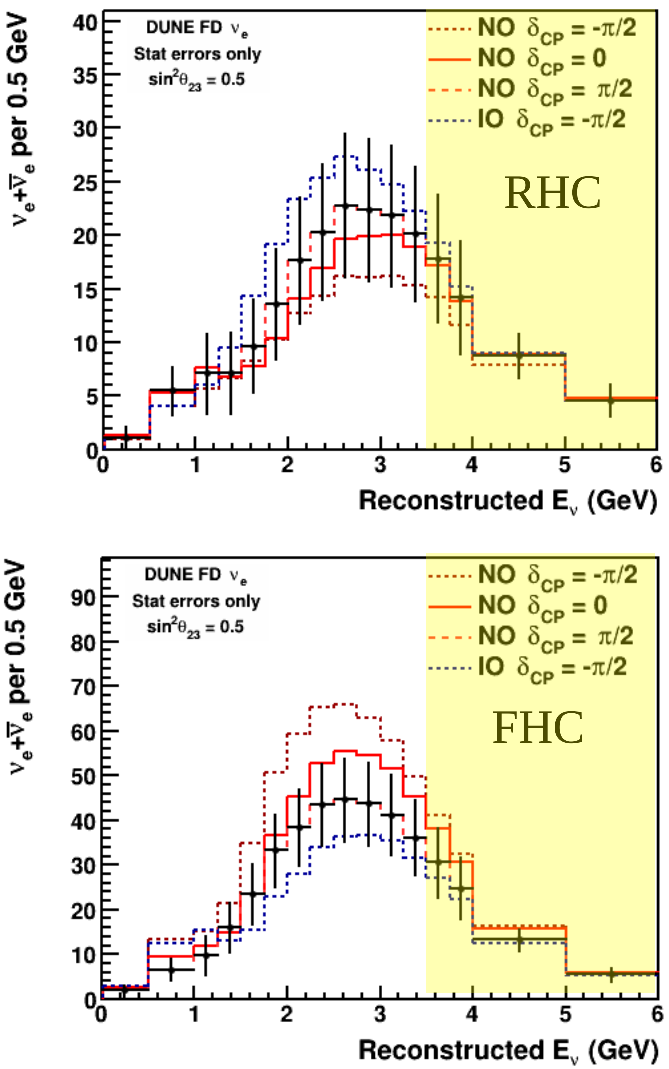


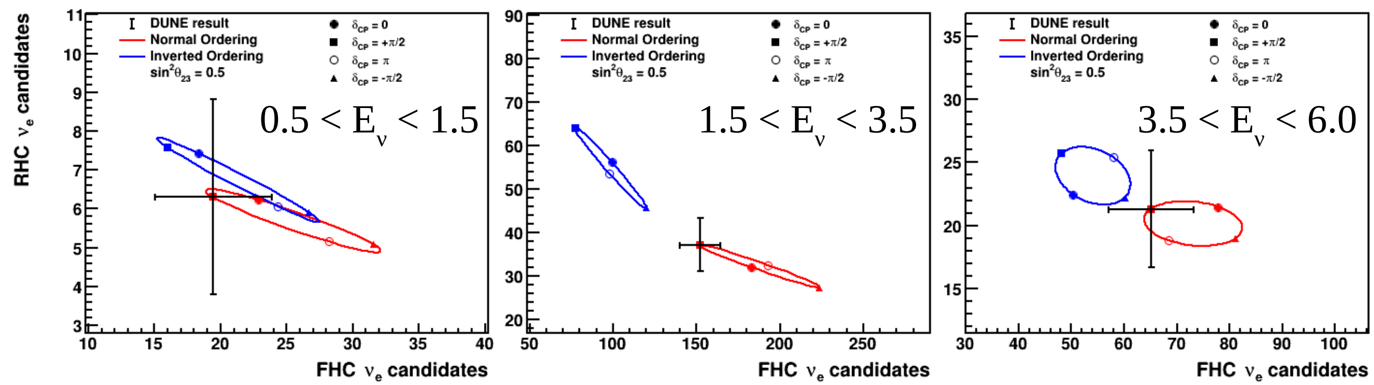




- In the oscillation maximum we have the largest effect due to the mass ordering
- However, there is a near-degeneracy between values of δ_{CP} on opposite sides of $\pm\pi/2$, i.e. between $\pi/4$ and $3\pi/4$

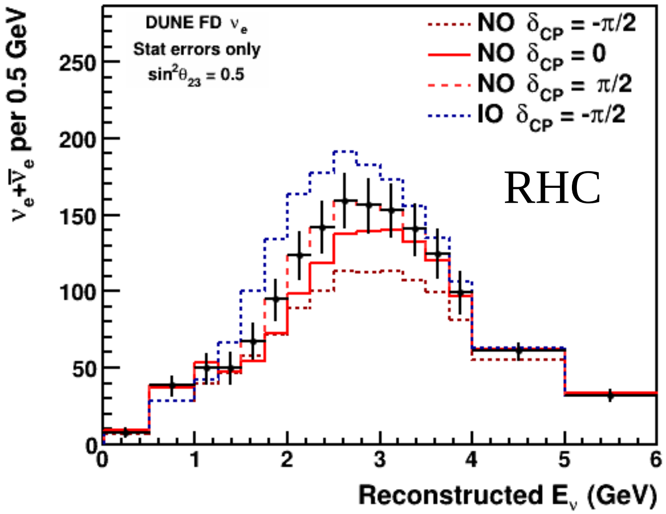
DUNE can do this in many energy bins over full oscillation period

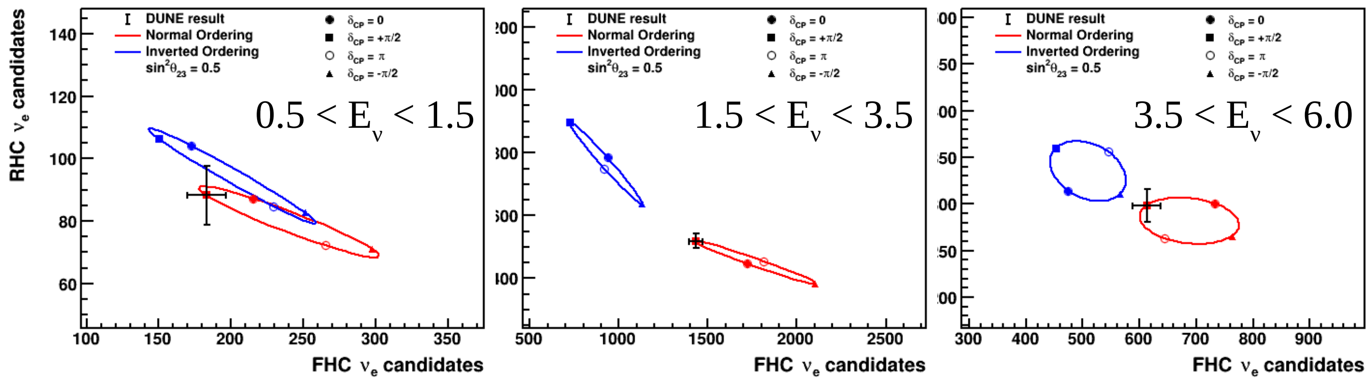


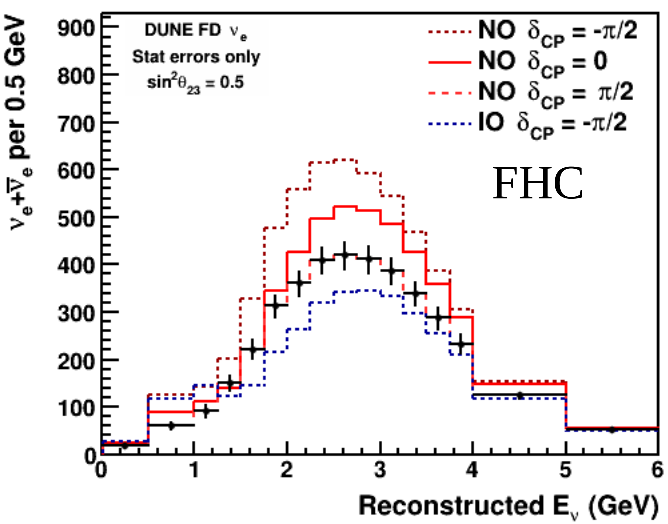


- By looking also at higher energy (L/E well below the oscillation maximum), this is resolved
- But making a precise measurement of δ_{CP} requires much higher statistics

DUNE Phase II: precision measurements of oscillations

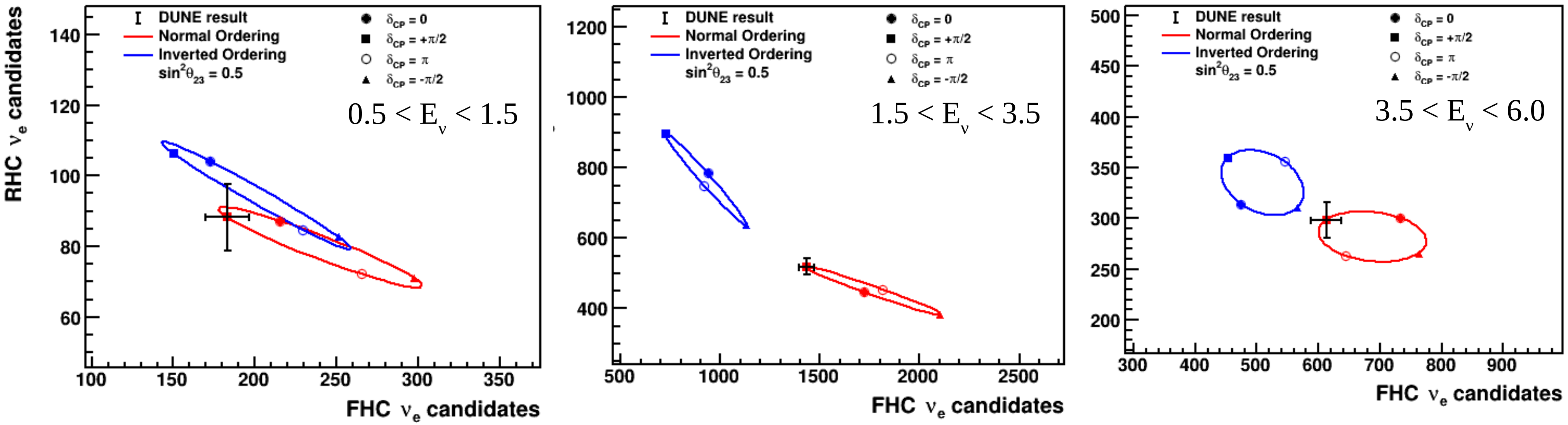






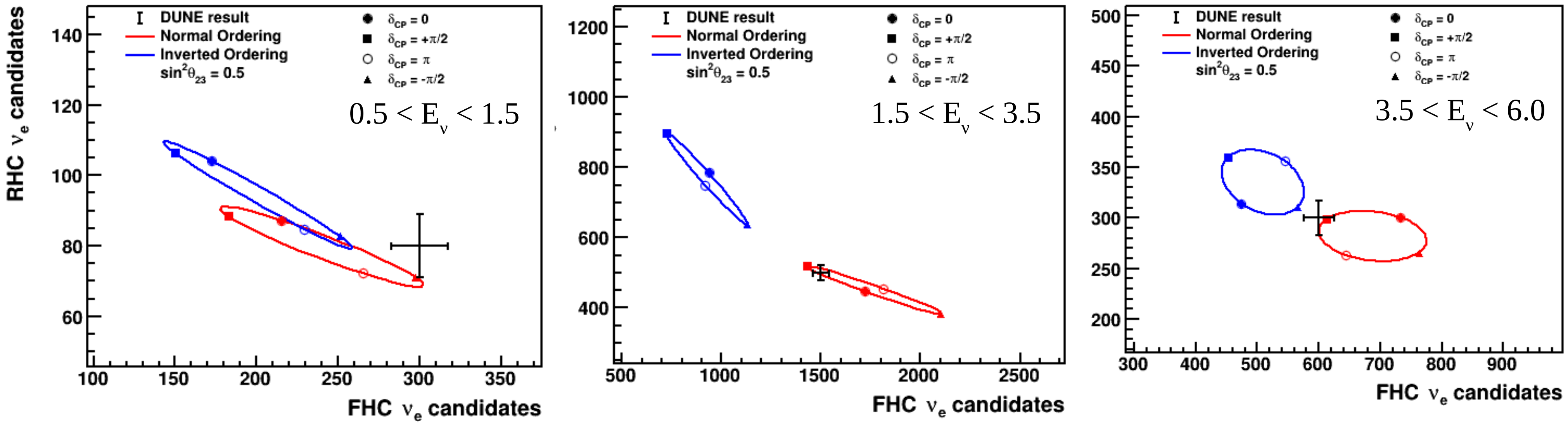
- This is what it will look like with DUNE Phase II
- We are not just determining the mass ordering and establishing CP violation anymore, we are measuring δ_{CP}

DUNE is extremely sensitive to new physics



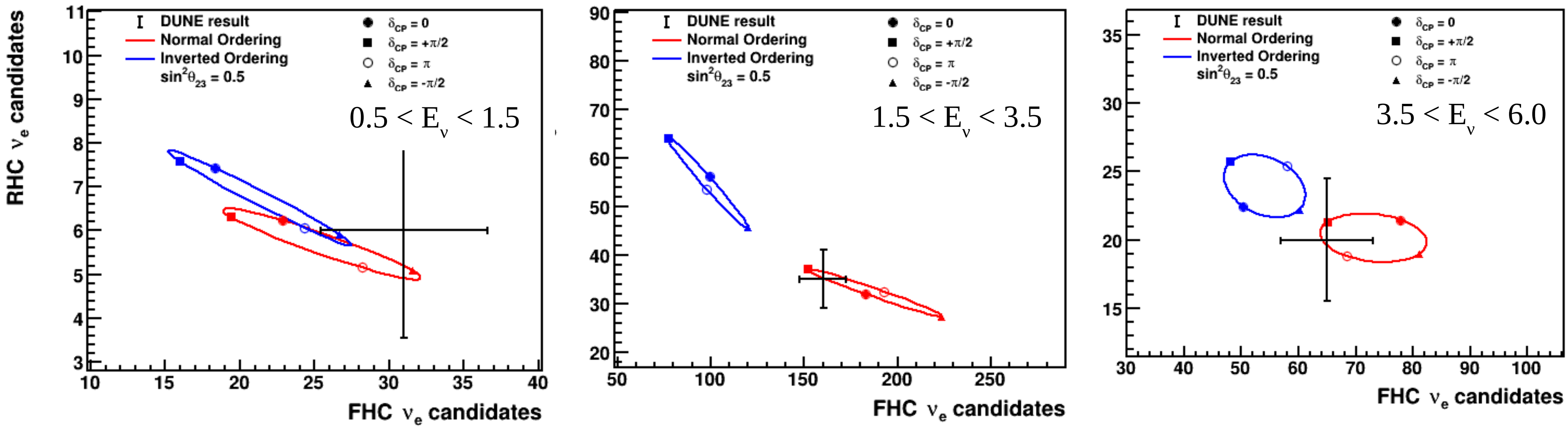
- If the three-flavor model is correct, oscillations depend only on L/E, and the data point will be at the same point on the same ellipse in every single energy bin
- We can search for deviations across a broad range of L/E

Example of definitive evidence of new physics



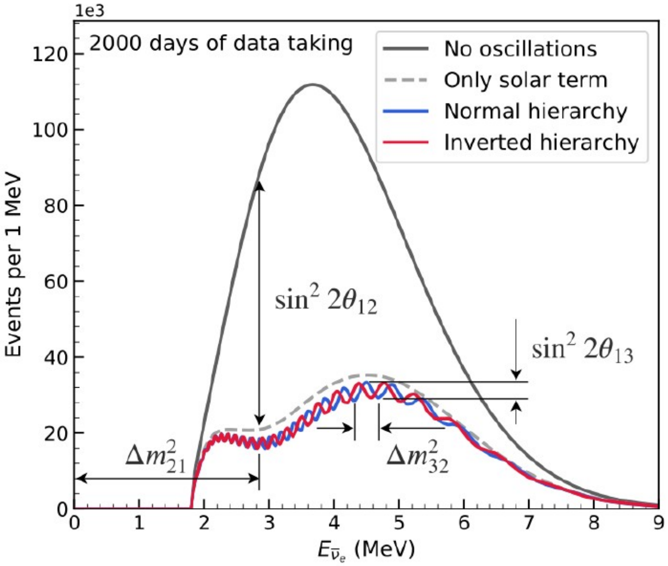
- We might see an anomaly only in a particular energy range
- Having broad L/E coverage with large matter effect is synergistic with Hyper-K
- Does this new physics depend on E rather than L/E? Is it matter dependent? Is it only present in the rapid oscillation region? Difficult to *characterize* the new physics with only one experiment, but DUNE + Hyper-K could probably answer all of these questions

With Phase I only, DUNE is not sensitive to new physics



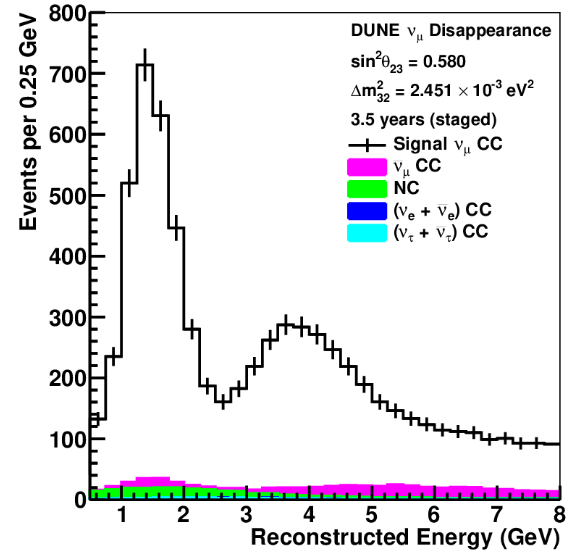
- Phase I statistical uncertainties do not permit this kind of new physics search – the data are consistent at 1σ with three-flavor oscillations for the same effect
- We have a fantastic opportunity to really push the three-flavor model, but it requires DUNE Phase II **and** Hyper-K

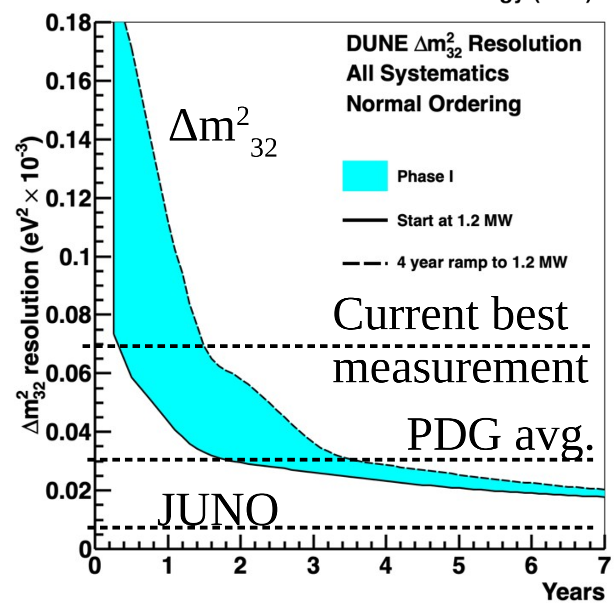
JUNO & DUNE Phase I: competition and complementarity



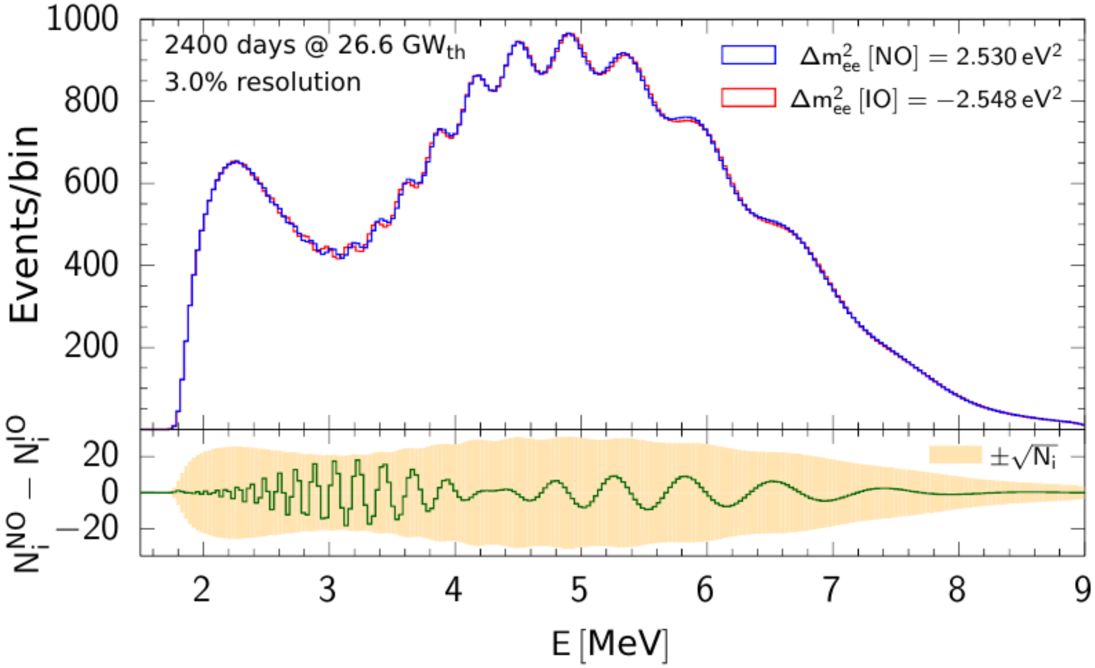
Δm^2_{31}	1σ (%)
Statistics	0.17
Reactor:	
- Uncorrelated	< 0.01
- Correlated	0.01
- Reference spectrum	0.05
- Spent Nuclear Fuel	< 0.01
- Non-equilibrium	< 0.01
Detection:	
- Efficiency	0.01
- Energy resolution	< 0.01
- Nonlinearity	0.04
- Backgrounds	0.04
Matter density	0.01
All systematics	0.08
Total	0.19

- JUNO sees a wiggle due to Δm^2_{32}
- Mass ordering is a phase
  - JUNO will probably have a ~3σ mass ordering observation when DUNE turns on
  - DUNE will catch up very quickly and reach 5σ far sooner
- Δm^2_{32} is a *frequency*, which JUNO can measure with incredible precision, ~4x better than current global fit
  - By the end of DUNE Phase I, we will have a ~0.2% measurement from $\bar{\nu}_e$, and a ~0.8% measurement from ν_μ
  - These are different transitions, but if our picture is complete we should get the same answer





Mass ordering in JUNO



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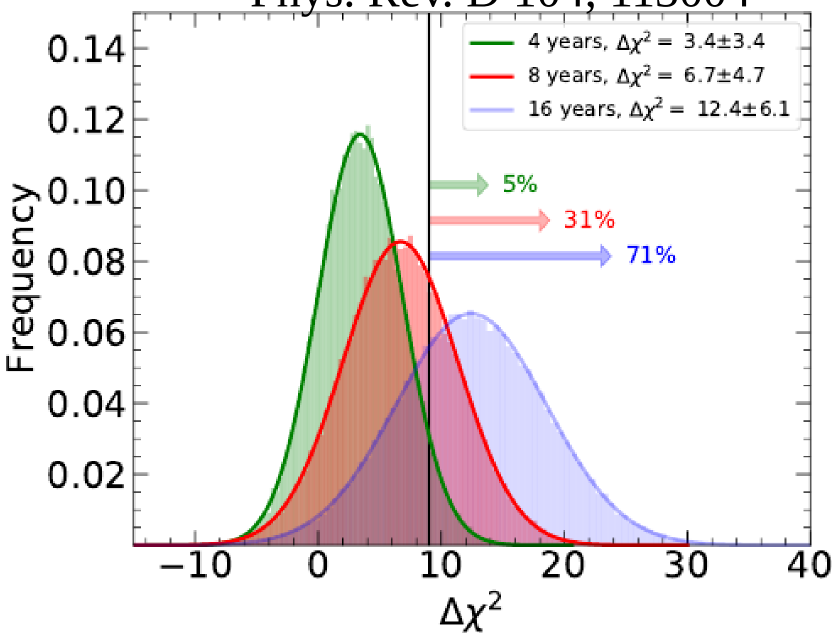
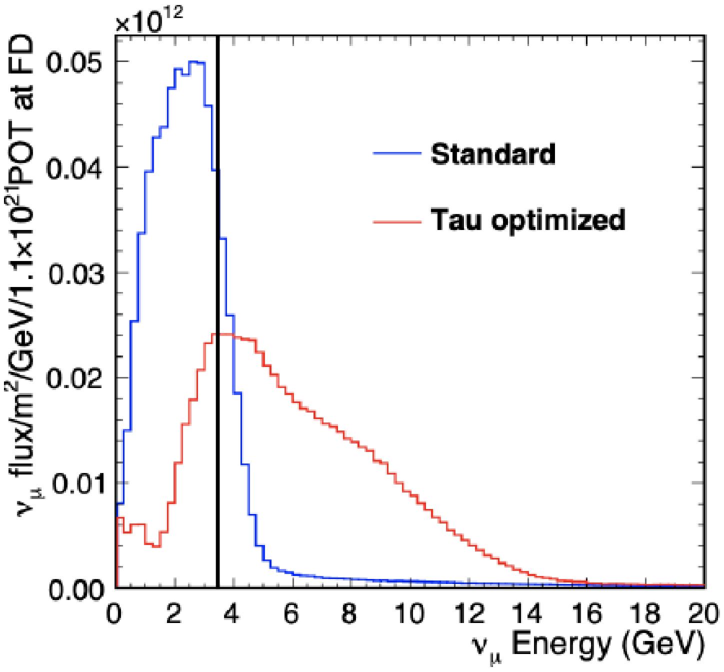
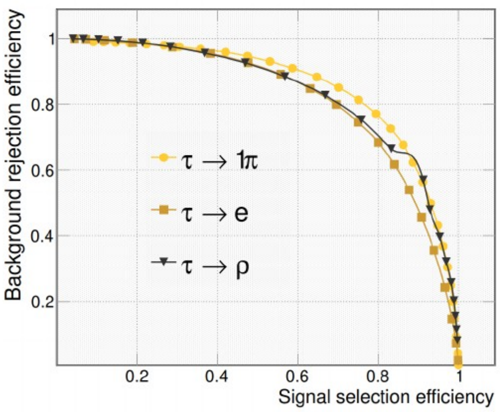


- Theory paper by Forero, Parke, Ternes, and Funchal studies the impact of various parameters (true values of oscillation parameters, energy resolution, nonlinearity, etc.) and shows how challenging MO measurement is in JUNO
- They conclude 31% chance of 3σ significance after 8 years (roughly when DUNE starts, assuming JUNO starts this year)
- This is somewhat (but not significantly) more pessimistic than JUNO’s published median sensitivity of 3σ in 6 years

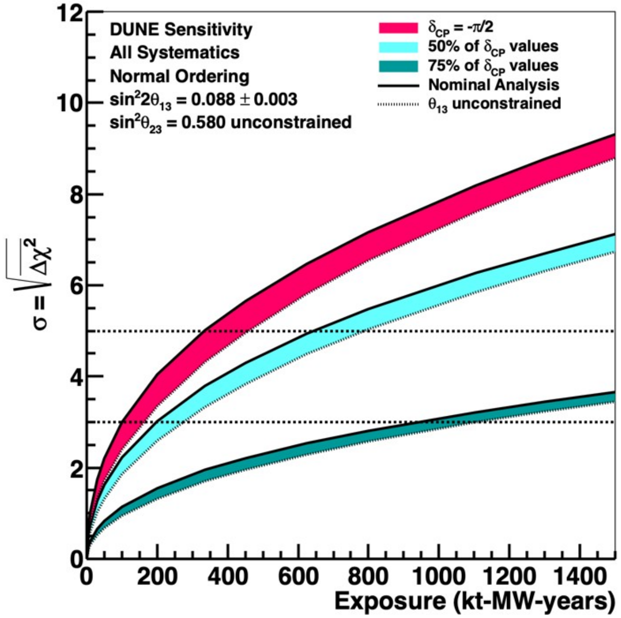
Unique to DUNE: three-flavor measurements, including taus

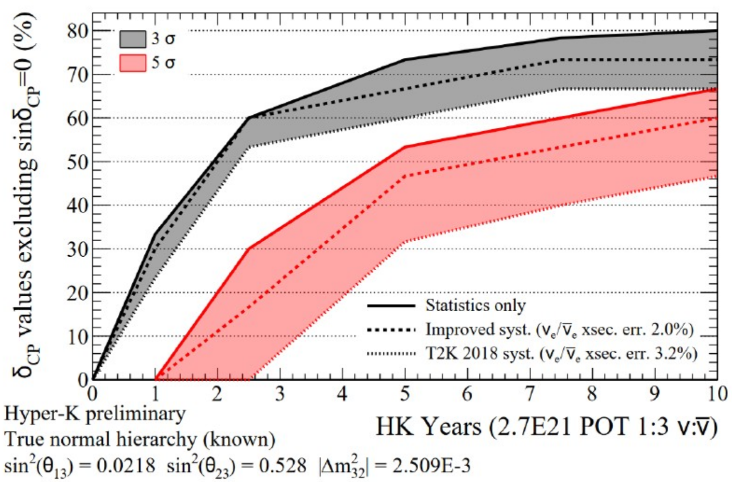




- Three-flavor unitarity tests are limited by the dearth of ν_τ data
- LArTPC presents a unique opportunity to image hadrons and improve the reconstruction of ν_τ CC interactions
- LBNF has significant flux above the τ production threshold, and the beam could be re-optimized (by moving the focusing components) to enhance ν_τ CC
- This is unique for accelerator beams, and complementary to atmospheric τ physics that is accessible in IceCube

When will CP violation be established?





- DUNE can establish CP violation at 3σ in 4 years (if δ_{CP} = 90°), or 6 years (δ_{CP} = 45°), or 14 years (if δ_{CP} = 22°), or establish that CP is **not** violated (if δ_{CP} = 0°)
- DUNE can establish CP violation at 5σ in 7 years (if δ_{CP} = 90°), or 10 years (δ_{CP} = 45°), or ~16 years (if δ_{CP} = 30°)
- With current T2K systematics, and assuming that J-PARC turns on at full power, Hyper-K can establish CP violation at 3σ in 1 year (if δ_{CP} = 90°), or 2 years (δ_{CP} = 45°), becoming systematically limited around δ_{CP} = 30°
- With "improved" systematics, 3σ reach goes out to ~24°
- For 5σ, depending on systematics Hyper-K can establish CP violation for δ_{CP} = 45° between 6-13 years, and becomes limited between 35-45°
- Hyper-K reach assumes that the mass ordering is determined externally

When will CP violation be established?

- Assuming that JUNO determines the mass ordering at 3σ by 2030, Hyper-K data begins in 2027 at full power, DUNE begins in 2031 with beam ramp-up and Phase II is pursued aggressively
- If δ_{CP} = 90°, CPV will be established at 3σ in 2030 by Hyper-K + JUNO, and at 5σ in 2032 by Hyper-K + DUNE
- If δ_{CP} = 45°, CPV will be established at 3σ in 2030 by Hyper-K + JUNO, and at 5σ in between 2034-41 by DUNE or Hyper-K (competitive, depending on systematics, with DUNE mass ordering)
- If δ_{CP} = 30°, CPV will be established at 3σ between 2033-2041 by Hyper-K or DUNE (competitive, Hyper-K will be first if systematics are improved significantly), and maybe at 5σ by 2047, or earlier if DUNE Phase II and Hyper-K combine
- If δ_{CP} = 22°, CPV will be established at 3σ between 2040-2045 by DUNE or Hyper-K, or possibly earlier if DUNE Phase II and Hyper-K combine
- If δ_{CP} = 0°, then DUNE and Hyper-K will measure δ_{CP} with a precision of ~6°

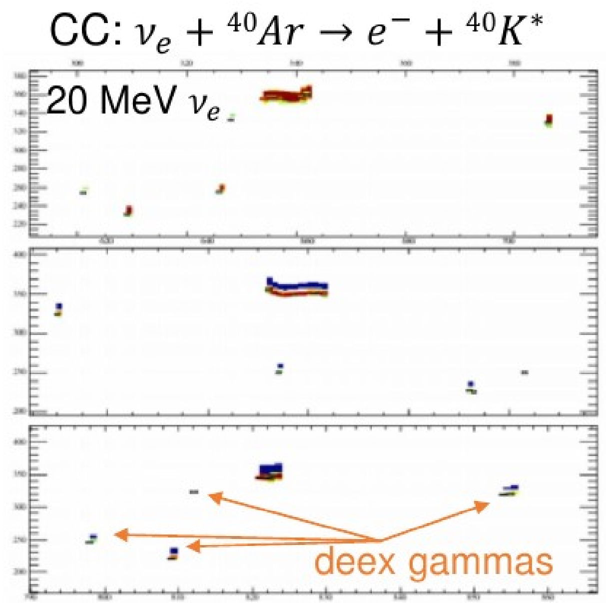
When will CP violation be established?

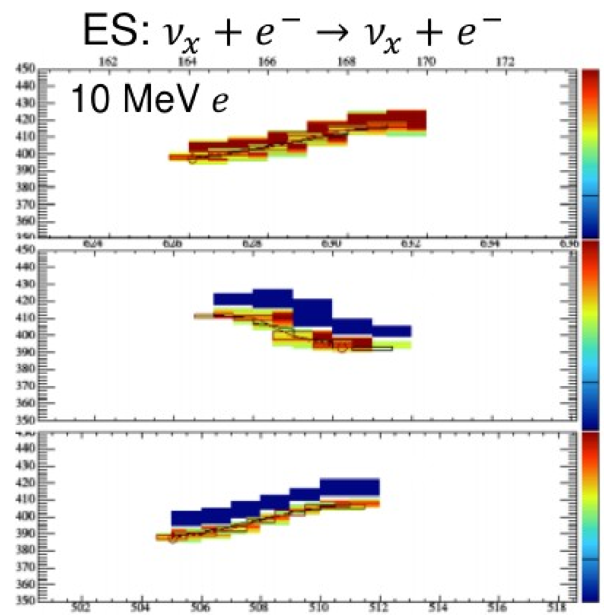
- Assuming that JUNO determines the mass ordering at 3σ by 2030, Hyper-K data begi Phase II is
- If δ_{CP} at 5σ in 20
- If δ_{CP} at 5σ in be matics, with DUNE mass ordering)
- If δ_{CP} r DUN signi er-K comb
- If δ_{CP} Hype
- If δ_{CP} = 0°, then DUNE and Hyper-K will measure δ_{CP} with a precision of ~6°

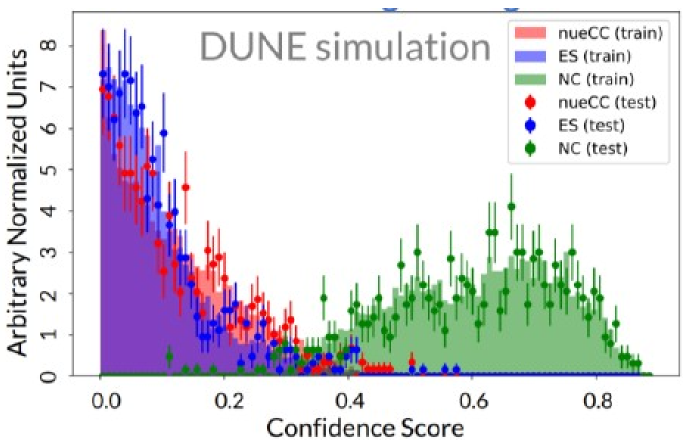
Nature is very kind:
Hyper-K establishes CPV
with mass ordering from JUNO (3σ)
or DUNE (5σ)

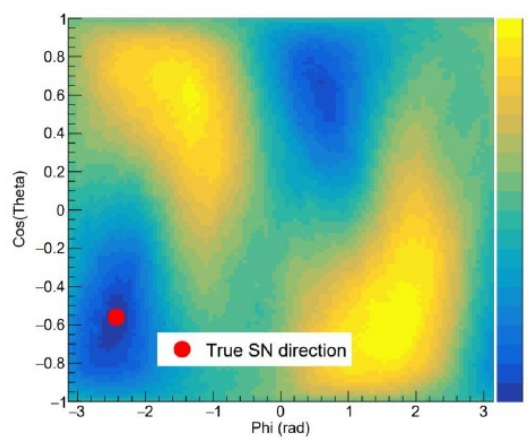
Nature is less kind:
DUNE and Hyper-K are competitive,
and both may be required

Supernova pointing in DUNE



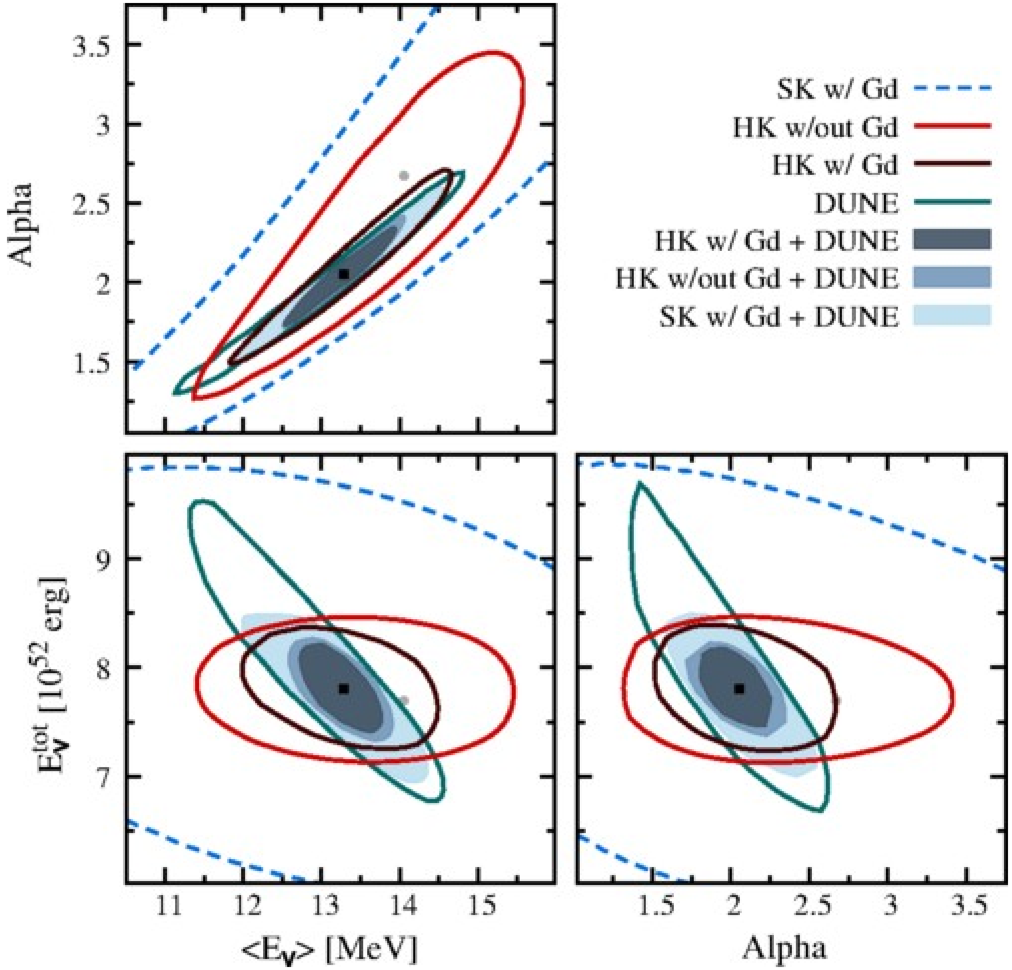






- DUNE can see low-energy de-excitation photons, which gives separation between charged-current (isotropic) and elastic scattering (very forward)
- Provides ~5° resolution
- The neutrino signal will arrive ~hours before light, DUNE can predict the location of supernovae

DUNE+HK complementarity: supernova neutrinos



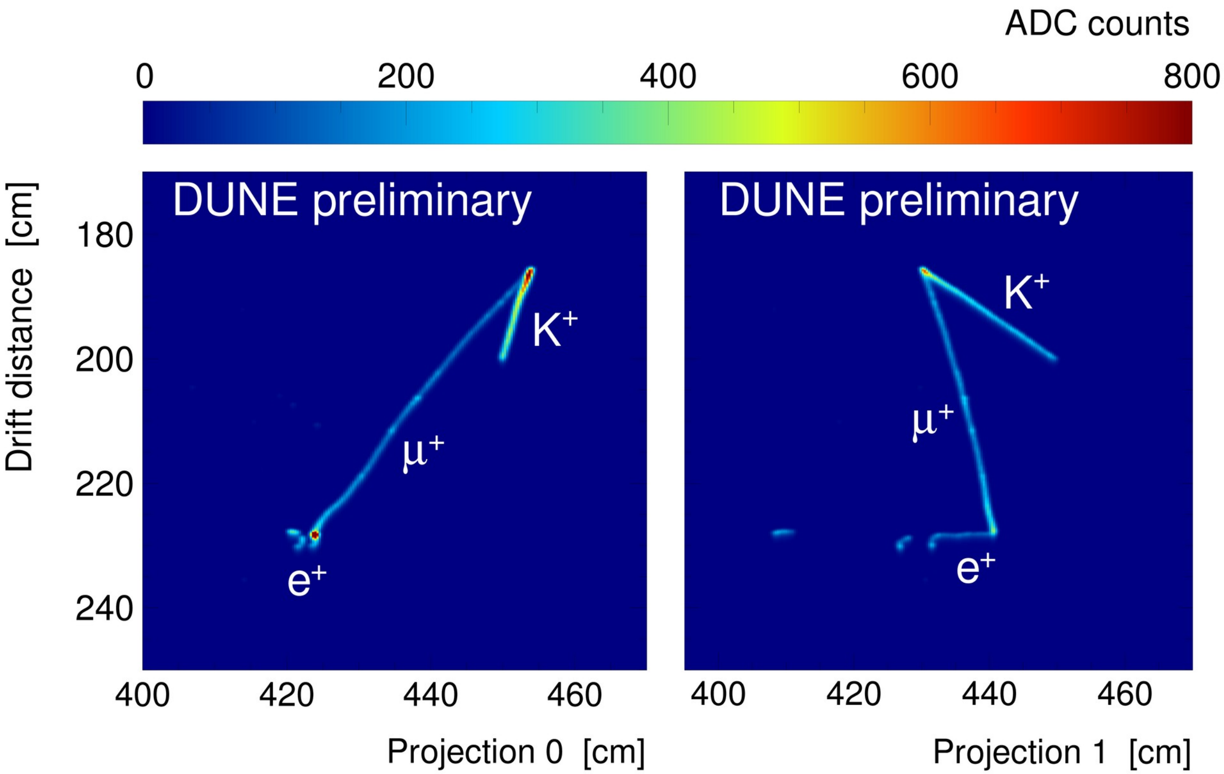
Nikrant, Laha, and Horiuchi
Phys. Rev. D 97, 023019

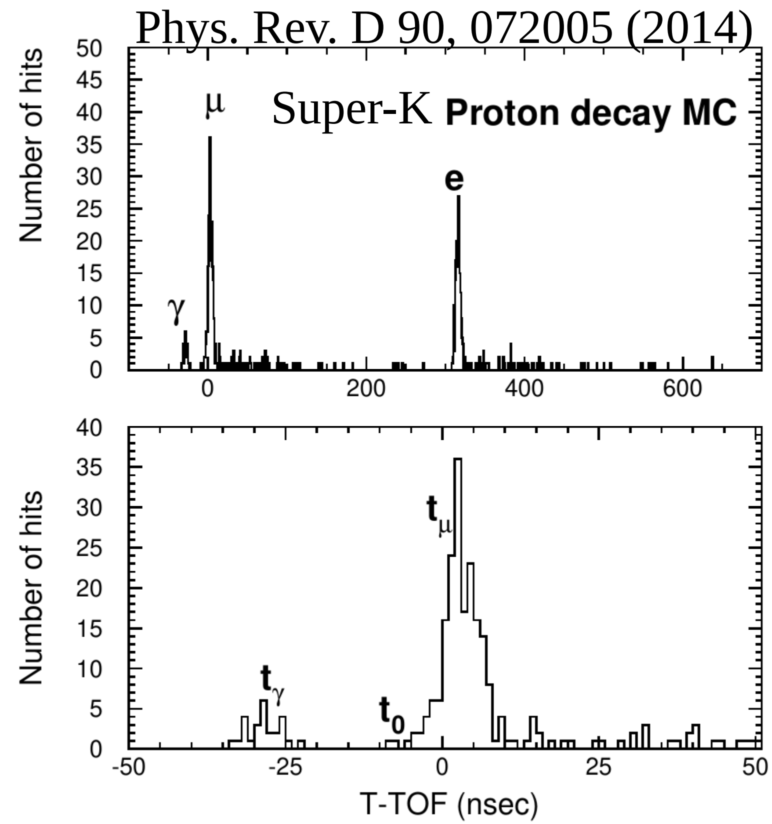
$$\frac{dN_\nu}{dE_\nu}(E_\nu) = A\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

$$A = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu\rangle\Gamma(\alpha+1)}$$

- Supernova spectrum can be parameterized by average neutrino energy and α
- DUNE and HK measure different fluxes → complementary ability to constrain spectral parameters
- DUNE Phase II (40 kt) shown in figure

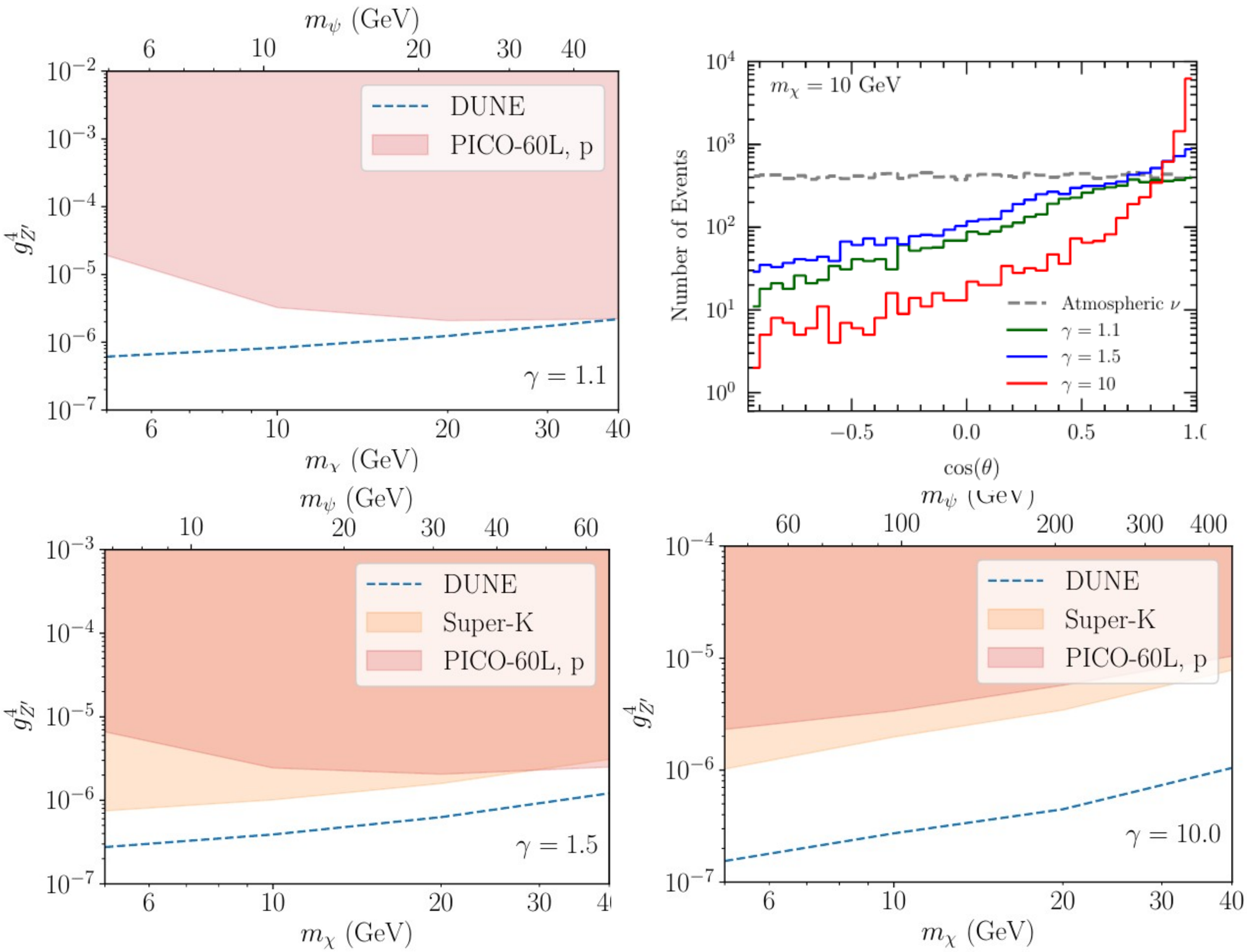
Nucleon decay p → K⁺ν





- Hyper-K can identify $p \rightarrow K^+\nu$ by timing, and identification of monoenergetic muon from kaon decay, with sensitivity to $\tau = 3 \times 10^{34}$ yrs
- DUNE can image all three particles, and has sensitivity beyond current Super-K limit (Phase II only)
- While DUNE is not competitive in exclusion reach, if a signal is observed in Hyper-K it will be extremely valuable to confirm the detection with a very different detector, different backgrounds, etc.

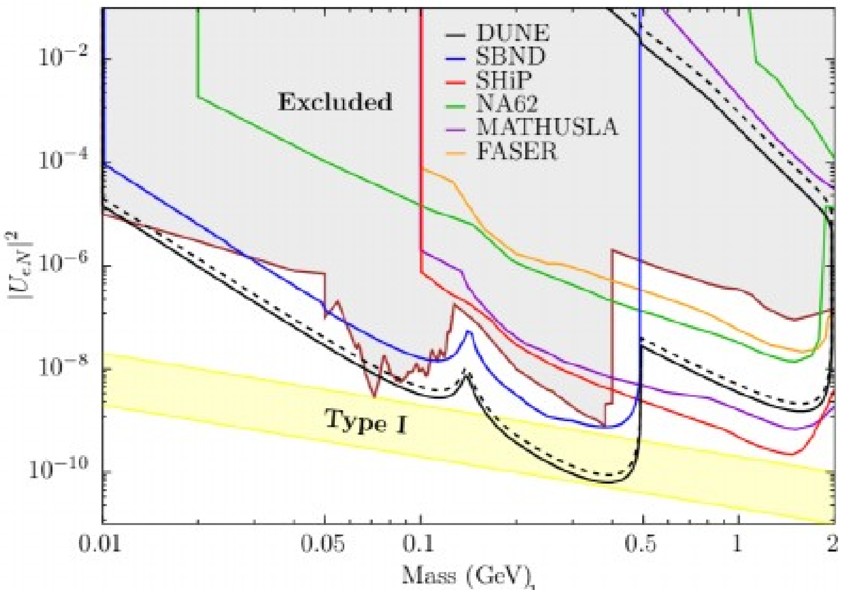
BDM from sun via hadronic channels

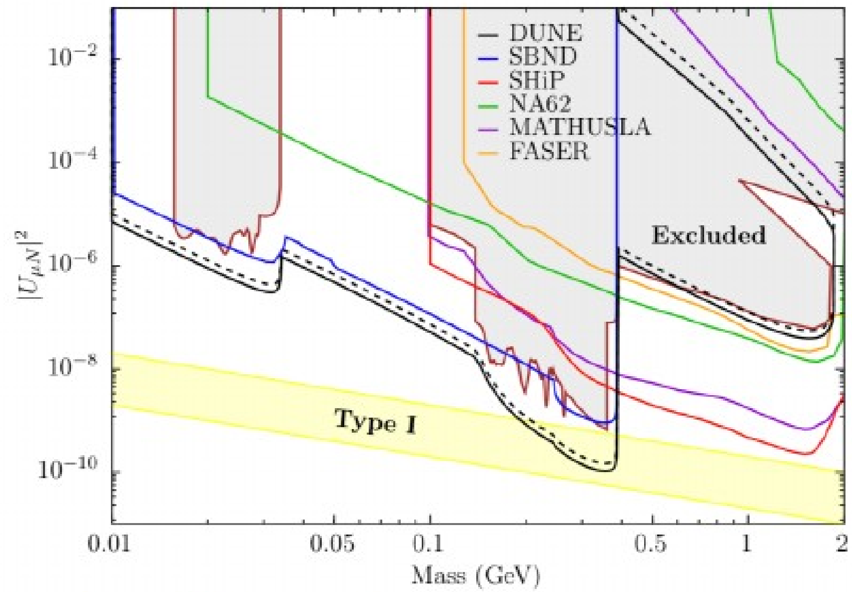


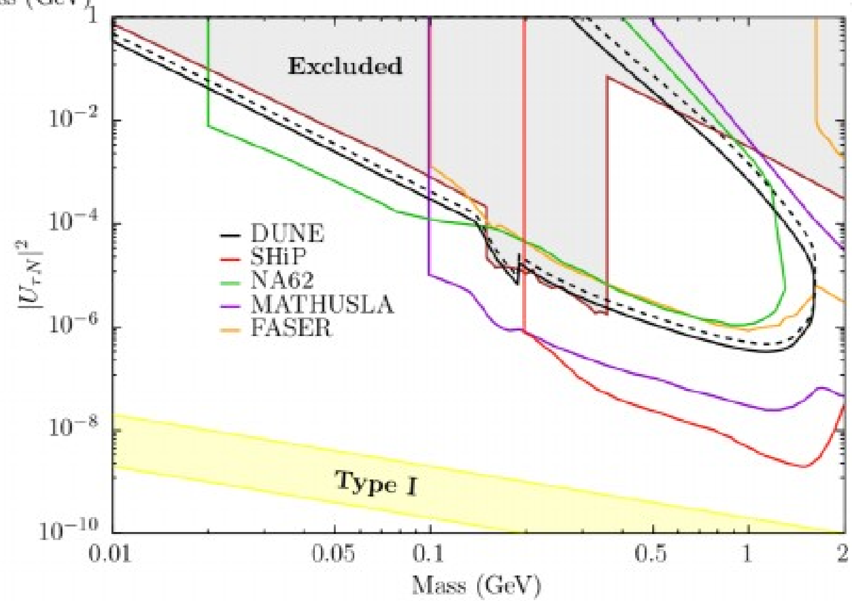
Phys. Rev. D 103, 095012 (2021)

- χN → χX hadronic processes
- Reconstruct direction in DUNE FD LArTPC, point back to Sun
- Low hadron thresholds are critical → at lower boost factors, SK/HK does not have sensitivity because protons are invisible
- DUNE can surpass current limits from PICO

DUNE HNL sensitivity at ND

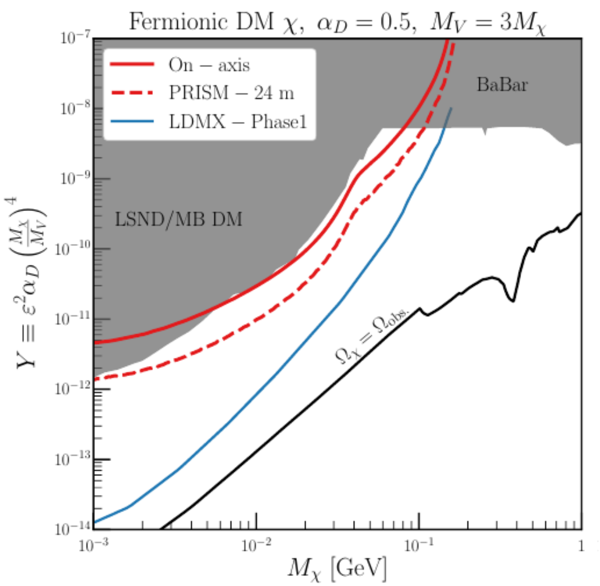


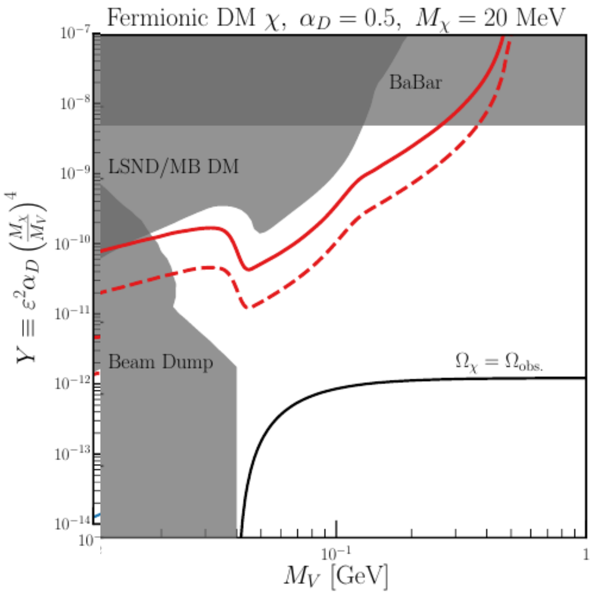




N → νee, $\nu e\mu$, $\nu\mu\mu$, $\nu\pi^0$, $e\pi$, $\mu\pi$
Phase II (22 MW-yrs)
no backgrounds → may require ND-GAr to reach zero background

BDM from the beam





- χe → χe scattering in ND-LAr, from boosted DM produced in the beamline
- Backgrounds from νe → νe have different spectrum
- DM and ν have different dispersion, and looking at off-axis ND-LAr data improves the statistical separation
- Sensitivity at low mass is potentially world-leading